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ABSTRACT

Title of Scholarly Paper: ANTARCTIC OPERATIONAL WEATHER FORECASTING

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The United States Antarctic Program (USAP) has maintained three year-round research stations on Antarctica since the 1950s. Research conducted on the continent has taken advantage of the unique conditions afforded by Antarctica's location and climate; unfortunately, these characteristics have also required an immense logistics operation by the USAP to support its researchers. Operation Deep Freeze, the airlift portion of this endeavor, is supported by units of the U.S. Air Force Reserve and Air National Guard. Flights to and around the continent require accurate operational weather forecasts to minimize the threat posed by Antarctica's harsh, highly variable weather. This paper reviews literature on significant Antarctic weather features, primarily katabatic winds and mesocyclones, around McMurdo Station, the hub of USAP aviation activities. It then describes the analysis and forecasting tools, specifically, Automatic Weather Stations, space-based remote sensing, and numerical weather prediction, used by USAP forecasters to create their weather forecasts. Problems with these tools and required improvements, including the Ross Island Meteorological Experiment, are also highlighted.

ANTARCTIC OPERATIONAL WEATHER FORECASTING

by

Sean Robert Keaveney

Scholarly Paper submitted to the Department of Meteorology of the University of Maryland, College Park in partial fulfillment of the requirements for the degree of Master of Science
2004

Advisor:
Professor Owen E. Thompson

The views expressed in this article are those of the author and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the U.S. Government.

1. Introduction

Antarctica's cold, pristine environment and remoteness make it a unique, valuable research location. Major advances in the fields of astronomy, biology, climate, geology, glaciology, meteorology, and oceanography [among others] have been made there in the last 40 years, and further breakthroughs are on the horizon. The National Science Foundation's United States Antarctic Program (USAP) has capitalized on Antarctica's research potential by establishing three year-round research stations [McMurdo, Amundsen-Scott South Pole, and Palmer] as well as several field camps during the austral summer. Unfortunately, Antarctica's research strengths are also its weaknesses. Its isolation, coupled with its extreme, highly variable weather, makes research in Antarctica a significant logistical challenge.

The backbone of the USAP's massive logistics operation is the heavy airlift capability of the U. S. Air Force Reserve and Air National Guard. Currently, the Air Force Reserve's 445th Airlift Wing [Wright-Patterson AFB] and 452nd Air Mobility Wing [March ARB], and the New York Air National Guard's 109th Airlift Wing [Stratton AGB] support this critical mission, known as Operation Deep Freeze. The primary role of the 445th AW and the 452nd AMW, who both fly the C-141C Starlifter, is to transport people and supplies into/out of McMurdo Station on Ross Island, the hub of the USAP's Antarctic activities. The 109th AW, with their ski-equipped LC-130H Hercules aircraft, is the sole logistical connection between McMurdo and the South Pole. Accurate weather forecasts in this hostile, erratic operating environment are vital for the success of the USAP's logistics operation and scientific research as well as for aviation safety.

In Chapter 2, a brief description of Antarctic geography is provided, while Chapter 3 is an overview of the USAP. The significant meteorological features of Antarctica that pose the greatest threat to aviation are described in Chapter 4. In Chapter 5, current observation, analysis, and forecasting tools/techniques are examined for both their respective contributions to successful Antarctic forecasting and problem areas that need to be addressed. Finally, Chapter 6 presents future improvements and research projects necessary to ensure continued success of the USAP's logistics operation in support of its ever-expanding research objectives in Antarctica.

2. Antarctic Geography

Antarctica is located completely beneath 60°S and is surrounded by the Southern Ocean. Its surface is primarily covered with ice, which accounts for 90% of the world's fresh water ice (King and Turner 1997). The continent can be divided into three distinct regions: East Antarctica, West Antarctica, and the Antarctic Peninsula, with the Transantarctic Mountains acting as a natural boundary between East and West (Fig. 1). East Antarctica has a fairly circular, symmetric form while West Antarctica is very sinuous, being dominated by the Antarctic Peninsula and two great embayments containing the Ross and Weddell Seas (King and Turner 1997).

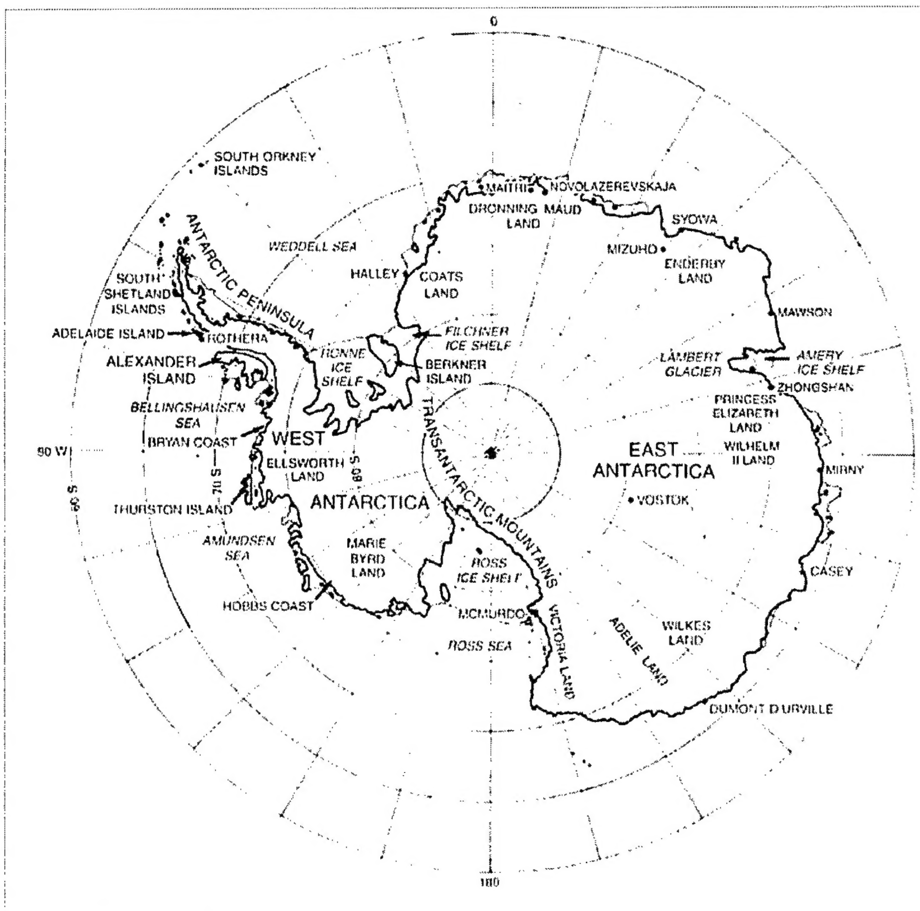

FIG. 1. Map of Antarctica showing principal regions and a selection of research stations (Turner and Pendlebury 2002).

East Antarctica, the largest region, contains the high Antarctic plateau. The interior of the ice sheet is above 2 km, with some areas reaching above 4 km (Fig. 2). The elevation of the ice gradually decreases northward with a rapid fall-off at the coast. In West Antarctica, with its two large ice shelves [Ross and Ronne], the ice sheet has a generally lower elevation, averaging 850 m (King and Turner 1997). In the mountainous area near the Ronne Ice Shelf, however, elevations range from 2 km to over 4 km. In fact, the highest point in Antarctica, Vinson Massif (4,897 m), is located here. The Transantarctic Mountains reach a maximum height of 4,528 m at Mt Kirkpatrick [near the Ross Ice Shelf]. The Antarctic Peninsula is a narrow mountainous barrier with an average height of 1,500 m and a mean width of 70 km (King and Turner 1997). Its highest point is Mt Jackson, 3,184 m, south of the Larsen Ice Shelf.

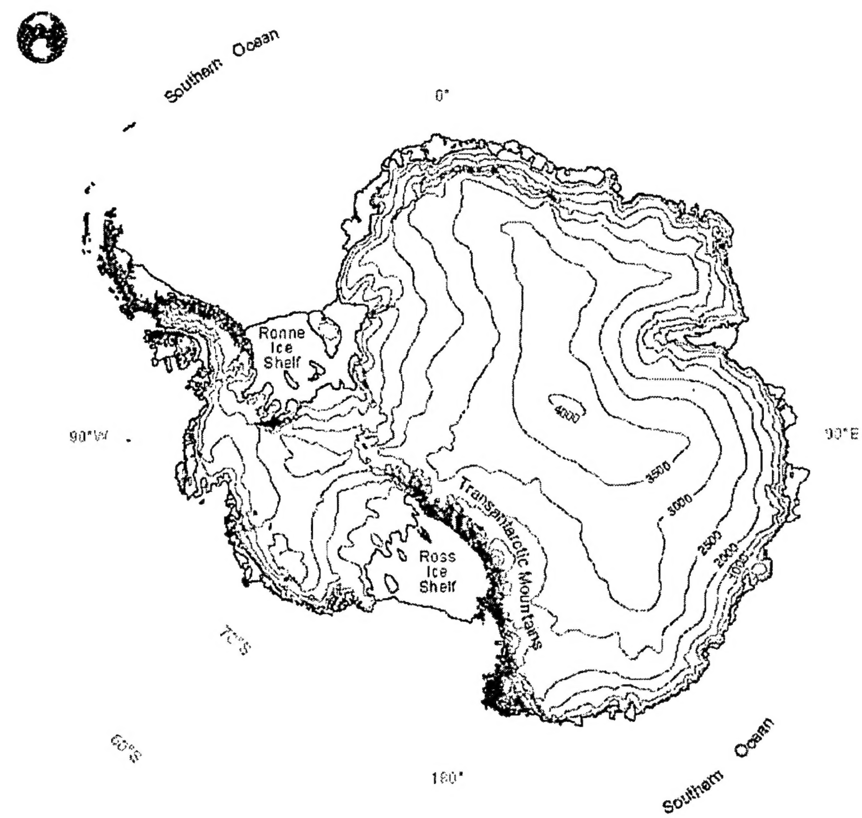

FIG. 2. Antarctic orographic contours at 500 m intervals (Turner and Pendlebury 2002).

The thickness of the Antarctic ice sheets varies over the continent. The greatest depth occurs in East Antarctica, approximately 400 km inland of the Dumont d'Urville research station, where the ice is 4,776 m thick (King and Turner 1997).

This paper is focused on the area of Antarctica between 150ºE and 120ºW, which contains Victoria Land, the Ross Sea, the Ross Ice Shelf, Marie Byrd Land, the Transantarctic Mountains, McMurdo Station and Amundsen-Scott South Pole Station.

3. United States Antarctic Program

The National Science Foundation (NSF), through its Office of Polar Programs, funds and manages the United States Antarctic Program (USAP), which oversees almost all of the U.S. scientific research in Antarctica. The USAP is comprised of scientists from U.S. universities and other research institutions, as well as contractors and U.S. Government agencies providing operations and support services, totaling approximately 3,000 Americans per year (NSF 2003a). The USAP was established in 1959, following the successful International Geophysical Year (IGY) of 1957-58. The IGY marked a new beginning in Antarctic research, replacing territorial claims with international cooperation toward free access to the continent for scientific research (King and Turner 1997). This new focus paved the way for the Antarctic Treaty, which is still in effect today.

The USAP is responsible for meeting our Nation's goals of: "supporting the Antarctic Treaty, fostering cooperative research with other nations, protecting the Antarctic environment, and developing measures to ensure only equitable and wise use of resources" (NSF 2003a). Additionally, the USAP's scientific goals are: "to understand the Antarctic and its associated ecosystems; to understand the region's effects on (and responses to) global processes such as climate; and to use Antarctica's unique features for scientific research that cannot be done as well elsewhere" (NSF 1999). To achieve these goals, the USAP maintains three year-round research stations in Antarctica: McMurdo, Amundsen-Scott South Pole, and Palmer. In addition, the program runs several field sites during the austral summer. During the 2003-2004 field season, the USAP supported 156 research projects in Antarctica and the Southern Ocean (NSF 2003b).

3.1. Research Stations

McMurdo Station [77°53'S 166°40'E] was established in December 1955 and is located on the bare volcanic rock of Hut Point Peninsula on Ross Island (NSF 1997a) (Fig. 3). It is the largest of the three American stations and is the center of all USAP activities in Antarctica. All personnel headed for the South Pole and the various summer field camps pass through McMurdo. The station includes a harbor, several landing strips, and over 85 buildings, ranging from radio shacks to the modern Albert P. Crary Science and Engineering Center (NSF 1997a). In addition to serving as the logistics hub for the USAP, McMurdo is an important research center. Areas of study include: "marine and terrestrial biology, biomedicine, geology and geophysics, glaciology and glacial geology, meteorology, aeronomy, and upper atmosphere physics" (NSF 1997a). In the summer, the station accommodates up to 1,200 people, while the winter population is about 250. The annual mean temperature is –18°C, with the monthly mean ranging from –3°C in January [summer] to –28°C in August [winter] (NSF 1997a).

FIG. 3. McMurdo Station from Observation Hill (Polar Meteorology Group, BPRC).

As the gateway to Antarctica, McMurdo has the most robust aviation facilities of all the USAP research stations, with three different airfields and a helicopter pad. The three airfields include: two 10,000 ft sea-ice runways (on annual sea-ice), two 10,000 ft skiways on the ice shelf [Williams Field], and one 10,000 ft permanent blue-ice runway [Pegasus] (NSF 2003c). The sea-ice runways, located within a mile of McMurdo, are operational from early October until late December, when the sea-ice becomes unstable.

They can accommodate heavy, wheeled aircraft. Once the sea-ice runways are closed, Williams Field is opened. These skiways are approximately 10 mi from McMurdo and are designed for ski-equipped aircraft only. Williams Field remains operational for the remainder of the austral summer. The last airfield, Pegasus, is 17 mi from McMurdo and is also utilized for wheeled landings. It is the first runway used at the start of the flying season and is operational throughout the summer.

FIG. 4. Amundsen-Scott South Pole Station (NSF, SSgt Lee Harshman).

Amundsen-Scott South Pole Station [90°S] is located on the high Antarctic plateau of East Antarctica, 841 statue mi from McMurdo (NSF 1999) (Fig. 4). It has been in continuous operation since November 1956 (NSF 1997b). The main part of the station is comprised of several buildings covered by a geodesic dome. Nearby, a 14,000 ft skiway accommodates ski-equipped aircraft from McMurdo. Currently, a renovation project is underway that includes the construction of a modern, elevated station that will "enclose 65,000 square feet of heated space, including offices, laboratories,…and private living quarters with windows for nearly every resident" (Blakeslee 2003). Upon completion, it will replace the dome. With its high elevation [2,835 m], low temperatures [annual mean of –49°C; monthly mean in December of –28°C and in July of –60°C], low humidity [less than 10%], and clear, homogeneous thick ice [2,850 m], the South Pole is ideal for

research in the fields of astronomy and astrophysics (NSF 1997b; Nordwall 1998). In addition, research is also conducted in "glaciology, geophysics, meteorology, upper atmospheric physics, and biomedical studies" (NSF 1997b). Amundsen-Scott has a summer staff of over 200, while only 50 scientists and support personnel winter over.

Palmer Station [64°46'S 64°03'W], located on Anvers Island on the western side of the Antarctic Peninsula, was established in 1965 (NSF 1997c) (Fig. 5). It is the USAP's smallest station, consisting of only a few buildings that support just over 40 people in the summer and about 10 in the winter (NSF 1997c). It is located above the Antarctic Circle and has the mildest weather of the three stations. The mean annual temperature is -3°C, with a July/August average of -10°C and a January/February mean of 2°C (NSF 1997c). Palmer, which has no designated airfield facilities, is logistically separated from McMurdo and Amundsen-Scott. It relies on the Research Vessel (R/V) Laurence M. Gould for transportation and supplies. The Gould makes several trips each season from its South American port of Punta Arenas, Chile. In addition to logistics, the R/V Laurence M. Gould "provides onboard research support in marine biology, oceanography, geophysics, and can support science in other areas of the southern oceans" (NSF 1999). At Palmer Station, research is performed in the areas of marine and terrestrial biology, meteorology, upper atmosphere physics, and glaciology (NSF 1997c).

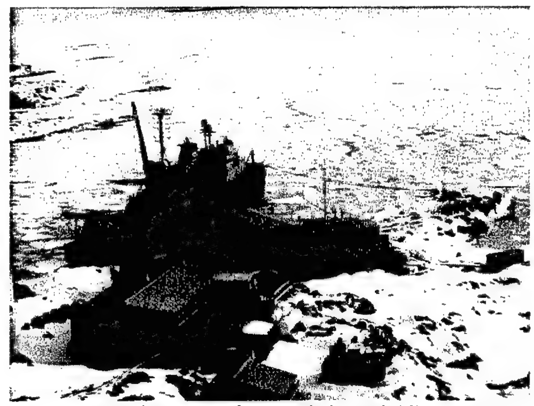

FIG. 5. Palmer Station and the R/V Laurence M. Gould (NSF, Jeffrey Kietzmann).

Since it is not logistically supported with USAP airlift assets, this paper does not address the Palmer region.

3.2. Logistics Overview

For all its research potential and strengths, Antarctica's location and environment pose severe logistical obstacles. To ensure scientists are successfully able to complete their work, the USAP funds and maintains a comprehensive logistics operation. In FY 2003, the overall USAP budget was "$254.95-million, of which $42.56-million was for research grants, $143.84-million was for operations and science support, and $68.55-million was for logistics" (NSF 2003b).

The logistics operation is spread among several civilian contractors and U.S. Government agencies. The USAP enlists Raytheon Polar Services Company to manage and coordinate the whole operation. The Department of Defense (DoD) receives funds from the NSF to plan and execute the following functions: "operating a squadron of LC-130 Hercules airplanes to support science projects and supply McMurdo and inland stations; arranging annually for a ship and a fuel tanker to supply McMurdo Station through the Military Sealift Command; conducting Military Airlift Command flights between Antarctica and New Zealand; and operating portions of a staging facility in Christchurch, New Zealand" (NSF 2000). Additionally, the Space and Naval Warfare (SPAWAR) Systems Center, Charleston (SSC Charleston) Aviation Technical Services and Engineering Division is tasked to provide meteorological support, air traffic control, and ground electronics maintenance on the continent and in Christchurch (Deitch 2003). The United States Coast Guard, an agency of the Department of Homeland Security, is

responsible for breaking a waterway through McMurdo Sound enabling the annual supply ship and fuel tanker to reach McMurdo Station and for escorting the ships into and out of the station (NSF 2000). In addition to the aircraft provided by the DOD, the USAP contracts two civilian companies to provide airlift support around McMurdo. Kenn Borek Air provides deHavilland DHC-6/300 Twin Otter aircraft while Petroleum Helicopters Inc. provides two types of helicopters [the Aerospatiale AS-350-B2 Squirrel and the Bell 212 civilian Huey] (NSF 2003c; NSF 1997e).

The USAP's logistics operation begins in late August and ends in late February. The two main components of the operation include the airlift provided by the DOD, known as Operation Deep Freeze, and the annual shipborne cargo/fuel resupply by the Military Sealift Command.

3.3. Operation Deep Freeze

Operation Deep Freeze is the backbone of the USAP's massive logistical operation in Antarctica. It is comprised of the heavy airlift capability of the U. S. Air Force Reserve and Air National Guard. The primary units/aircraft involved in Deep Freeze are: the Air Force Reserve's 445th Airlift Wing (AW) and 452nd Air Mobility Wing (AMW), who both fly the C-141C Starlifter, and the New York Air National Guard's 109th AW, who operate the ski-equipped LC-130H Hercules. Occasionally, other aircraft are used, such as the C-17 Globemaster III and the C-5 Galaxy, depending on the particular airlift mission. For comparison purposes, the table below lists the maximum loads of cargo and passengers for the Christchurch-McMurdo flight for the different aircraft used in Operation Deep Freeze. During the 2003-2004 season, C-141Cs

Aircraft	Maximum Cargo Load	Passengers
C-5 Galaxy	150,000 pounds	73
C-17 Globemaster III	120,000 pounds	102
C-141C Starlifter	42,000 pounds	140
LC-130H Hercules	10,500 pounds	36

TABLE 1. Maximum loads of cargo and passengers for Christchurch-McMurdo flight (NSF 2003b).

transported 1.6 million pounds of cargo and 3,446 passengers to and from McMurdo, logging more than 426 flying hours (Theopolos 2004).

The intercontinental flights of people and supplies between Christchurch, New Zealand and McMurdo Station are the responsibility of the 445th AW and the 452nd AMW, although the 109th AW also participates. The flights between McMurdo and Amundsen-Scott, however, are the sole responsibility of the 109th. Other intra-continental flights, to the various summer field camps, are handled by the 109th as well as the Twin Otters and helicopters contracted by the USAP. During Operation Deep Freeze, the 445th and the 452nd are stationed out of Christchurch, while the 109th, Twin Otters, and helicopters are based at McMurdo. Flight totals for the 2003 – 2004 season can be found in Table 2:

LC-130 missions (round trips) within Antarctica	
Amundsen-Scott South Pole Station	331
Summer field camps	70
Total LC-130 missions	401
Twin Otter missions within Antarctica	122
Helicopter operations within Antarctica	2,321.3 flight hours
Christchurch-McMurdo round trips	
C-17 Globemaster III	15
C-141C Starlifter	41
LC-130H Hercules	12

TABLE 2. Flight totals for Operation Deep Freeze aircraft, 2003 – 2004 season (NSF 2003b, 2003c; RPSC 2003a, 2003b; Theopolos 2004).

Operation Deep Freeze is flown in three phases. The first phase, called WINFLY because it occurs late in the austral winter [end of August], transports "scientists and support personnel to start early pre-summer projects, to augment maintenance personnel, and to prepare skiways and ice runways at McMurdo Station" (NSF 2003c). This phase consists of roughly 3 flights [C-17, C-141, or C-5] into McMurdo from Christchurch. The second phase supports austral summer activities. Flights from Christchurch deliver necessary supplies and personnel. Flights into the continent transport research teams and their cargo to various field sites and to the South Pole. The final phase, redeployment, occurs at the end of the austral summer. All aircraft leave the continent by the end of February.

This paper is confined to operational weather forecasting for Operation Deep Freeze missions, specifically activities in and around McMurdo Station.

4. Significant Meteorological Features

Antarctica is the coldest, windiest, highest, driest, and iciest continent on Earth. Its weather is "characterized by extremes: extreme temperatures, extreme winds, and extremely variable localized conditions" (McCormick 2002). Accurate weather forecasts are critical for successful Operation Deep Freeze missions, efficient logistical operations, and the safety of USAP personnel.

The flight from Christchurch to McMurdo is 2,100 nautical mi, which can take from 5 to 8 hours, depending on the aircraft flown (Nordwall 1998; Deitch 2003). The length of this mission puts the aircraft at the mercy of Antarctica's severe, rapidly changing weather. According to Col. David Walker, from the 4th Air Force operations division at March Air Reserve Base, CA, "Operation Deep Freeze 'missions are the most difficult missions we operate in a non-combat environment because there is no margin for error'" (AFPN 2003). Missions are flown with very stringent weather restrictions to ensure safety and success. Prior to takeoff, the navigator determines the farthest south the plane can fly and still make it back to Christchurch safely (Miller 2001). When that point is reached during the flight, the aircrew calls McMurdo and if the current arrival forecast has changed to include weather conditions outside specific minimums, the flight returns to Christchurch [known as a "boomerang"].

While the flight from McMurdo to the South Pole only takes approximately 3 hours [728 nautical mi], it is also susceptible to Antarctica's varying weather (Miller 2001; NSF 1997d). With no other well-groomed airfields/skiways available in Antarctica besides McMurdo and the South Pole, poor weather at Amundsen-Scott forces the LC-130s to take one of four alternatives: fly a holding pattern until conditions improve, land

at a semi-prepared skiway at a large field camp, return to McMurdo, or just land somewhere that looks smooth and hope there are no hidden crevasses (Miller 2001; Nordwall 1998). Hazardous weather at McMurdo leaves the aircrew with similar options plus the opportunity to use the designated 'whiteout area'. This area is a crevasse-free section of snow, near McMurdo, where the LC-130s can land from any direction (Nordwall 1998).

On average, boomerangs and aborted flights account for about a dozen or more of the 600 - 700 missions flown annually; however, they result in a considerable financial loss, typically $25,000 to $80,000 each (Roth and Lazzara 2002). In addition, they waste time, disrupt the logistics schedule, and increase the safety risk for USAP personnel. It is essential to keep these situations to a minimum. On the other hand, canceled missions for forecasted bad weather that does not occur are just as costly, although the risk to USAP personnel is diminished. Due to the limited flight season and the substantial role Operation Deep Freeze missions play in the USAP's logistics operation, it is imperative that the significant weather-producing phenomena around McMurdo Station are known and understood so accurate and reliable operational weather forecasts can be created.

4.1. McMurdo Station and Hazardous Aviation Weather

McMurdo Station's weather is heavily altered by local effects, the greatest of which is its complex topography (Fig. 6). Within 50 km of the station, elevations rise from sea level to over 3,000 m (Bromwich and Cassano 2001). McMurdo is "further complicated by the convergence of three differing zones: a permanent ice sheet, a polar

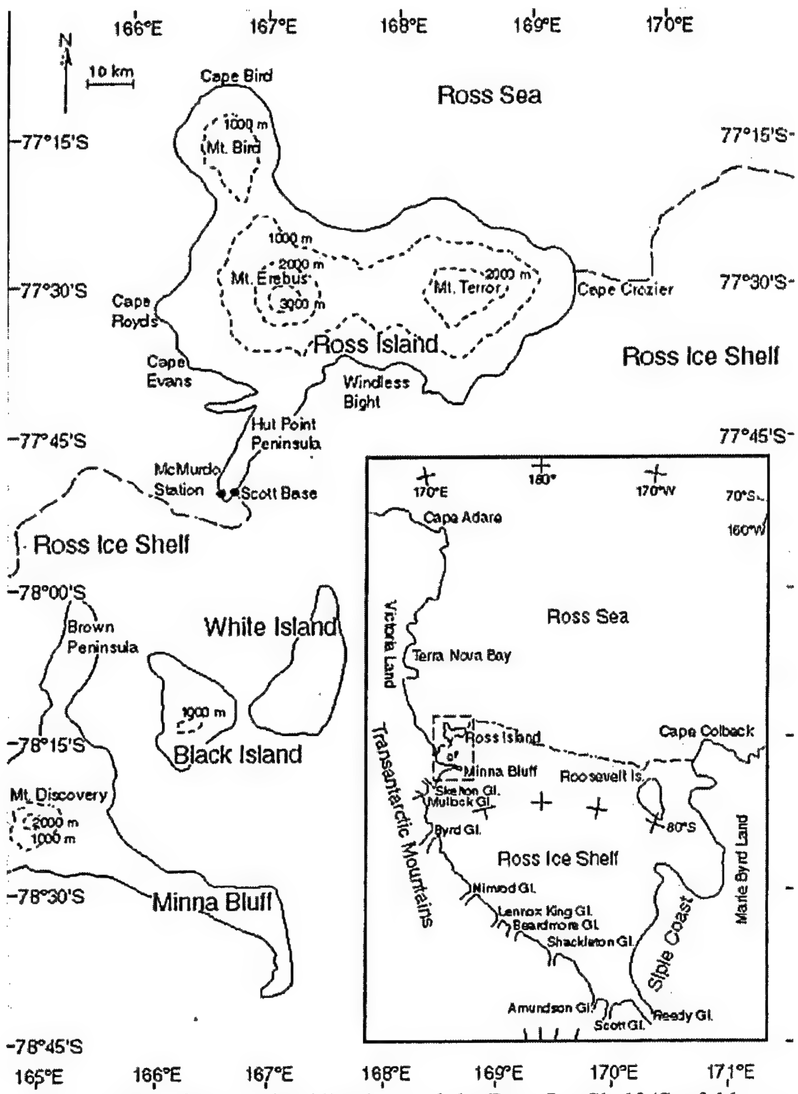

FIG. 6. Map of Ross Island Region and the Ross Ice Shelf (Seefeldt et al. 2003).

plateau and the Transantarctic Mountain Range, and the open waters of the Ross Sea, which can extend down the west side of Ross Island and in anomalously warm summers, even around McMurdo itself" (Fogt 2003). All of these factors combine to make weather forecasting for McMurdo a unique and challenging task.

McMurdo's forecasters are particularly concerned with the following weather events, which pose the greatest threat to aviation: fog, precipitation, high winds, blowing snow, turbulence, and icing. Fog is by far the most common cause for poor aviation weather at McMurdo (Roth and Lazarra 2002). The station's proximity to the cold Ross

Ice Sheet and the warmer water of the Ross Sea make it ripe for fog development. While fog has occurred during all months of the year, it is the most prevalent in the summer months, after the sea-ice around Ross Island has broken up. In general, warm, moist air from the Ross Sea is advected over the cold ice sheet into the Windless Bight, an area of naturally divergent surface winds, where it condenses into fog and then expands into the McMurdo area (Turner and Pendlebury 2002). The fog reduces visibilities low enough to suspend aircraft operations at McMurdo's airfields.

Precipitation, in the form of snow, is a year-round event at McMurdo, with a peak in the summer months as a result of the seasonal availability of moisture from the Ross Sea and the warmer air temperatures (Turner and Pendlebury 2002). The precipitation is normally associated with some type of synoptic or mesoscale feature. The warmer temperatures allow the snow to become moist (larger flakes), which can cause, in calm winds, a greater reduction in visibility [< 3,200 m] than its winter counterpart [> 4,800 m] (Turner and Pendlebury 2002). The most dangerous precipitation event at McMurdo is the hurricane-force blizzard, known as a Herbie. These storms, which contain extremely strong winds, arrive quickly and reduce the station to whiteout conditions and Weather Condition I: "Winds over 55 knots, wind chill lower than -100°F, or visibility less than 100 feet; severe weather in progress; all personnel must remain in buildings or the nearest shelter" (McCormick 2002). Herbies can approach from any direction, but they are most likely to come from the south, moving between Black and White Islands, which is aptly named Herbie Alley.

The general surface wind-flow pattern on the Ross Ice Shelf is from the south. The flow at McMurdo, however, is easterly due to the orographic influence of Ross

Island (Turner and Pendlebury 2002). During high wind events, greater than 20 m s^{-1}, the orographic shaping of the winds will diminish and the flow will move over obstacles, giving McMurdo a southerly wind (Seefeldt et al. 2003). These winds tend to be strong from the surface up to 1,500 – 2,000 m. McMurdo winds are also subject to pressure systems over the Ross Sea, which can overpower the general wind pattern.

High wind speeds are the origin of a few aviation-related problems at McMurdo. First, wind speeds of 15 m s^{-1} or greater will pick up snow from the surface, even if it is well packed, and blow it as high as 100 m, reducing the visibility at McMurdo to less than 1,600 m (Monaghan 2002). Blowing snow can also occur with weaker winds, greater than 10 m s^{-1}, if the snow surface is new. Second, winds above 20 m s^{-1} will produce light to severe turbulence from the surface to 1,500 m (Turner and Pendlebury 2002).

Finally, aircraft icing is possible during the flying season with the increase in moisture caused by the break up of sea-ice on the Ross Sea. Icing conditions are present with nimbostratus clouds and are normally light to moderate rime icing, although there have been rare cases of moderate mixed icing (Turner and Pendlebury 2002).

Most of these conditions do not exist alone, but are the consequences of larger forcing. The two most significant meteorological features that support this restrictive aviation weather in and around McMurdo Station are katabatic winds and mesocyclones.

4.2. Katabatic Winds

When a surface cools radiatively, the air near the surface becomes colder and denser than the air aloft, thereby achieving negative buoyancy. When this process occurs

over sloping terrain, the cold, dense air close to the surface responds to the buoyancy force and accelerates down the slope. This downslope flow is known as a katabatic wind. This type of flow is common in the mid-latitudes as well as in Antarctica. Mid-latitude katabatic winds only happen at night and are considered a small-scale feature of the boundary layer (King and Turner 1997); however, in Antarctica, the katabatic winds are unique. Antarctica's consistent, cold, stable boundary layer and overall dome-shaped topography allow katabatic winds to control the year-round low-level circulation across the continent (Fig. 7).

The general circulation pattern has the winds moving coastward from the polar plateau, turning left under the effect of the Coriolis force and merging with the coastal polar easterlies (King and Turner 1997). Wind speeds are correlated to the degree of terrain slope: the steeper the slope [coastal areas], the higher the speeds. Their flow direction is also determined by topography, as the interior winds tend to follow the topographic features, while most coastal winds have varying directions. This is a function of the degree to which synoptic and meso-scale features influence the wind regime. The interior is relatively blocked from these impacts, but the coast is not. This results in an interior flow that is characterized by persistent, directionally constant winds, but a coastal flow that is a combination of katabatic and synoptic/meso-scale forcings. In general, the

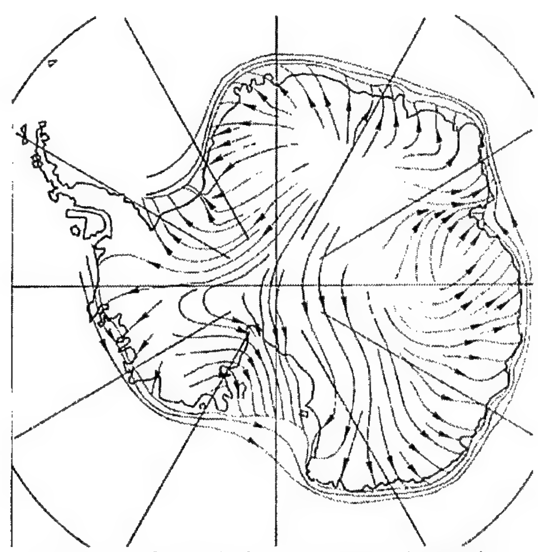

FIG. 7. Surface wind streams over Antarctica (King and Turner 1997).

katabatic winds are more intense during the austral winter when the surface radiative cooling and stable boundary layer are both at their peak.

Antarctica's katabatic flow is well known for producing extremely strong, sustained winds. Specific points along East Antarctica's coast are especially famous for their high winds, which routinely reach hurricane force. Cape Denison, on the coast of Adélie Land, has a mean annual wind speed of 22 m s^{-1} [50 mph] and its maximum winds have approached 89 m s^{-1} [200 mph] (GLACIER 1998). Douglas Mawson's expedition, based at Cape Denison, recorded gale force winds on all but one of 203 consecutive winter days during 1912 – 1913 (King and Turner 1997). While places like Cape Denison are extreme, the remainder of coastal Antarctica has mean winds of only 5 – 10 m s^{-1} (King and Turner 1997). The reason behind the constrained locations of intense coastal winds is local topography.

In order to have sustained, strong katabatic winds at the coast there must be a large supply of cold, dense air inland. The radiatively cooled air formed in the interior could not support long-term katabatic winds along the entire coast; therefore, this type of wind event must be a localized feature (King and Turner 1997). While researching surface winds over East Antarctica, Parish (1982) discovered an interesting drainage pattern as the winds approached the coast. The streamlines of the flow converged in certain areas, one of which was upstream of Cape Denison. Parish (1982) concluded that the positioning of this confluence zone would provide Cape Denison with a "nearly inexhaustible supply of cold air", which flows through a narrow topographic gap at the coast, allowing for the formation of the persistent, strong katabatic winds observed there. He also found another confluence zone upstream of Terra Nova Bay, where similarly

intense, prolonged katabatic winds have also been observed. Bromwich and Kurtz (1984) investigated the confluence zone theory for Terra Nova Bay's katabatic winds. The winds at this location are important for two reasons: first, they help to form and maintain a large polynya [open water in the ice] throughout the winter, and second, the winds are linked to mesocyclone development, which will be discussed in the next section.

Parish and Bromwich (1987) capitalized on an updated, accurate topographic map of Antarctica to calculate the near-surface wind pattern over the whole continent. Their results further verified the confluence zones found by Parish (1982) as well as identified several others, specifically a zone near the Byrd Glacier [southwest portion of the Ross Ice Sheet] and a zone near the Siple Coast [southeast portion of Ross Ice Sheet] (Fig. 8).

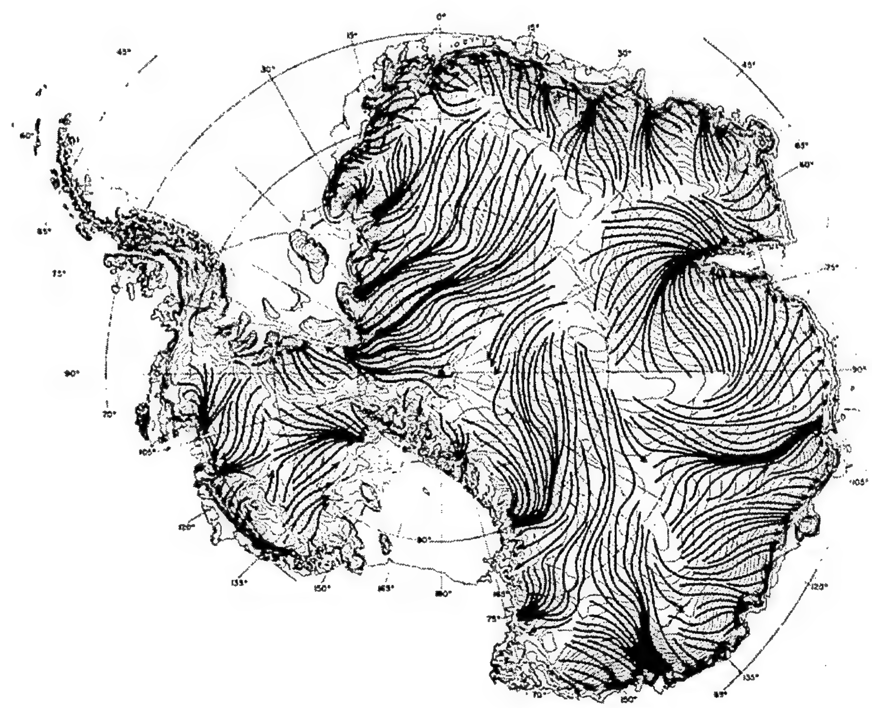

FIG. 8. Simulated streamlines of katabatic wind drainage (Parish and Bromwich 1987).

Two main features are responsible for the wind pattern at McMurdo Station: katabatic flow through the confluence zones at Byrd Glacier and the Siple Coast as well

as from the many minor glaciers that are part of the Transantarctic Mountains, and barrier winds formed along the Transantarctic Mountains. During the flying season, the katabatic winds flow down onto the Ross Ice Shelf, but are generally weaker than their winter counterpart. The katabatic winds from the glaciers in the Transantarctic Mountains flow north towards the east side of Ross Island and are deflected by the topography around McMurdo.

The winds from the confluence zone near the Siple Coast will, with no synoptic or meso-scale pressure gradient present, both turn to the left under the Coriolis force and be retarded by surface friction as they flow across the Ross Ice Sheet (King and Turner 1997). This will force them up against the Transantarctic Mountains, but they will not be able to flow over them. The cold air will continue to pile up, deepening toward the obstacle, creating a pressure gradient perpendicular to the barrier (King and Turner 1997). This will form a northward flowing barrier wind [the mountain on its left]. If a synoptic cyclone is in the Amundsen Sea, its pressure gradient will act to balance the Coriolis force and overcome friction. This will allow the katabatic winds from the Siple Coast to flow over 1,000 km across the Ross Ice Shelf, reaching the Ross Sea near Ross Island, without significant deceleration or change in direction (King and Turner 1997). This phenomenon is known as a katabatic surge.

Barrier winds will also form if either a synoptic or meso-scale cyclonic feature is present over the central Ross Ice Sheet or southern Ross Sea. In this case, the easterly winds of the cyclone will be forced against the Transantarctic Mountains (O'Connor et al. 1994) along with the katabatic winds. This type of barrier wind is primarily responsible for aviation hindering high wind speed events at McMurdo.

The katabatic winds at Terra Nova Bay have an indirect effect on McMurdo's surface winds. These katabatic winds remain fairly strong throughout the summer and have been tied to meso-scale cyclogenesis. These cyclones can move toward the McMurdo area, depending on the upper-level synoptic structure, and create the powerful barrier winds detailed above.

The confluence zones near Terra Nova Bay, Byrd Glacier, and the Siple Coast all play an important role in the surface flow experienced at McMurdo Station. Additionally, they all can form mesocyclones, which can severely degrade aviation conditions at McMurdo.

4.3. Mesocyclones

Mesocyclones are relatively short-lived, sub-synoptic-scale low-pressure systems that occur in both Polar Regions. They generally exist for less than 24 h and have a horizontal extent under 1,000 km, both of which make mesocyclones difficult to forecast. Despite their ability to produce dangerous weather and hazardous conditions over the oceans and coast of Antarctica, their existence was unknown until the advent of satellites [due to the sparse surface observational network] (King and Turner 1997). Furthermore, research into this phenomenon of Antarctic meteorology was not started until high-resolution satellite imagery was readily available for this region in the early 1980s (King and Turner 1997). For this reason, mesocyclones are not understood to the level that has been achieved for Antarctica's synoptic features; however, recent research is helping to close this gap as well as to clarify the role of mesocyclones in Antarctica's complex weather regime.

Typical Antarctic mesocyclones are cold air vortices with diameters less than 500 km and lifetimes less than 12 h. Their cloud patterns, as observed from satellite images, can be classified into two categories: spiraliform and comma-shaped (King and Turner 1997). Spiraliform mesocyclones have a circular, symmetric pattern with several cloud bands ringing the low center, while the comma-shaped mesocyclones have a comma-shaped appearance with the head of the cloud near the center of the low and the tail stretching toward higher pressure (King and Turner 1997). The formation of these two types of mesocyclones is based on the level of synoptic support present, spiraliform cyclones form in areas with no synoptic forcing, whereas comma-shaped lows need strong synoptic flow (Turner and Pendlebury 2002). Mesocyclones develop throughout the year along the coast of Antarctica, over its ice shelves, at the northern edges of sea-ice, and over the ice-free Southern Ocean (Carrasco et al. 2003; Simmonds et al. 2003).

In their study, Carrasco et al. (2003) used one year [1991] of digital Advanced Very High Resolution Radiometer (AVHRR) satellite imagery to conduct a survey of mesoscale vortices between 160°E and 10°W. They determined the overall Ross Sea/Ross Ice Shelf region was the most active area (Fig. 9). Their results, which were normalized to an equal unit area of 10,000 km^2, revealed: 5.0-6.0 mesoscale vortices (10,000 km^2)$^{-1}$ yr^{-1} in the area around Terra Nova Bay, 3.0-4.0 vortices (10,000 km^2)$^{-1}$ yr^{-1} near Byrd Glacier, and 2.0-2.9 (10,000 km^2)$^{-1}$ yr^{-1} above the southernmost part of Marie Byrd Land [Siple Coast].

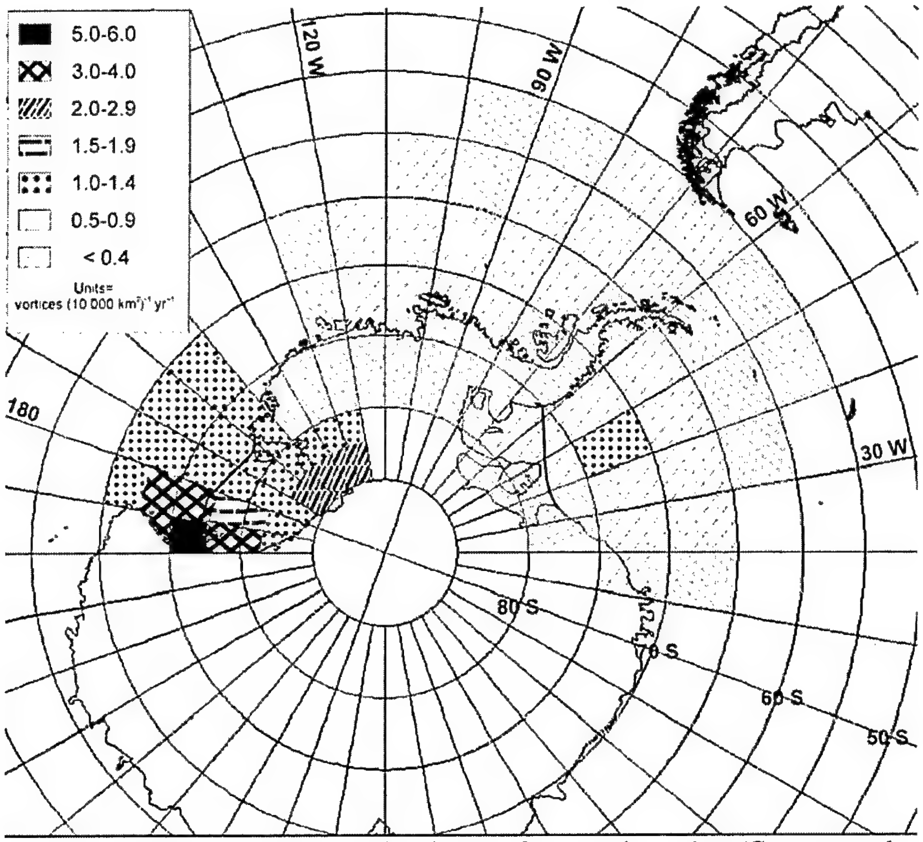

FIG. 9. Annual area-normalized distribution of mesoscale vortices (Carrasco et al. 2003).

Table 3 summaries the satellite characteristics for these three areas as well as the Ross Sea and the Ross Ice Sheet:

Type	TNB	RS	BG	RIS	SC
Comma type (%)	50	45	36	65	63
Avg diameter (km)	200	195	267	247	279
Deep vortices (%)	12	9	4	2	0

TABLE 3. Satellite characteristics of areas within Ross Sea/Ross Ice Shelf region: TNB, Terra Nova Bay; RS, Ross Sea; BG, Byrd Glacier; RIS, Ross Ice Shelf; SC, Siple Coast (Carrasco et al. 2003).

On average, half the mesoscale vortices are comma-shaped. Carrasco and Bromwich (1994) found a greater prevalence, above 70%, for comma-shaped mesocyclones in these areas [minus the Siple Coast] during 1988. These results indicate the importance of strong synoptic support to mesocyclone activity in the Ross Sea/Ross Ice Shelf region.

The horizontal extents of the vortices are all below 300 km and only a small percentage of the total are considered deep [defined by Carrasco et al. (2003) as containing middle/white cloud signatures on a grayscale satellite image]. The lack of vertical growth, most of the vortices do not exceed the 700-mb level, points to stable conditions. The stability of the Ross Sea/Ross Ice Shelf region is a by-product of the katabatic winds that flow through this area (described in Section 4.2).

Carrasco et al. (2003) also compared monthly distributions during 1991 and found the greatest mesoscale activity occurred in the austral summer. In addition, they observed that the annual average weekly mesoscale cyclone formation equaled two to three in Terra Nova and one to two in Byrd Glacier. This matches results found by Bromwich (1991) and Carrasco and Bromwich (1994).

In order to assess 1991's activity against other years, Carrasco et al. (2003) compared the synoptic situation during that year to climatology. Since mesoscale cyclogenesis is a function of synoptic variability, this type of comparison would identify how far 1991's activity varied from climatology. They found that the Ross Sea/Ross Ice Shelf region's sea level pressure anomaly was nearly zero, indicating that mesocyclone activity for 1991 was close to climatology. Therefore, the mesoscale cyclone activity observed in this region is not an anomalous characteristic, but the general state of affairs.

The process of mesocyclone formation and development is not understood completely, at present, although there are certain factors that appear to be important: baroclinic instability, barotropic instability, vortex stretching, surface fluxes of heat and moisture, and low-level convergence (Turner and Pendlebury 2002; Gallée 1995). The top three areas of mesoscale cyclone activity highlighted by Carrasco et al. (2003) [Terra

Nova Bay, Byrd Glacier, and the Siple Coast] are capable of providing most of these factors through their respective confluence zones and the resultant katabatic wind regimes they create.

Baroclinic instability, in Antarctica, is a result of "moderate-to-strong low-level thermal gradients" (King and Turner 1997). Katabatic winds in the three areas produce low-level baroclinicity by transporting cold air from East Antarctica to the warmer air over the Ross Sea and Ross Ice Shelf, establishing a baroclinic zone that can initiate mesocyclone formation (Carrasco and Bromwich 1993, 1994; King and Turner 1997; Carrasco et al. 2003; Heinemann and Klein 2003). Gallée (1995) conducted a numerical simulation over the southwestern Ross Sea [Terra Nova Bay area] to "determine if pure katabatic winds [were] able to force mesocyclonic activity during the open water season (February-March)". He found that the katabatic winds formed boundary layer fronts [baroclinic zones] that played an important role in the formation and deepening of southwestern Ross Sea mesocyclones. Bromwich (1991) used AWS data and satellite images to study mesoscale cyclogenesis at Terra Nova Bay and Byrd Glacier. He noted that both regions were active mesocyclone areas and were located in regions of intense discharge of cold East Antarctic boundary-layer air. He found that both baroclinicity and cyclonic vorticity, in the boundary layer, were linked to the high mesoscale cyclone activity in the areas. Although the confluence zone over the Siple Coast differs dynamically from those near Terra Nova Bay and Byrd Glacier, Bromwich and Liu (1996) found that a baroclinic zone could form "where the northern edge of the cold East Antarctic katabatic flow meets the edge of the warmer katabatic flow from West Antarctica".

Barotropic instability as a mechanism for mesoscale cyclone formation was found in the Terra Nova Bay region. Numerical studies by J. Carrasco found mesocyclones formed south of the low-level katabatic jet near Terra Nova Bay (Carrasco et al. 2003). This region, south of the katabatic winds, is associated with cyclonic shear and therefore is a source of barotropic instability, which, in this simulation, acts as the initial trigger for mesocyclone activity (Carrasco et al. 2003).

The stretching of vertical air columns helps produce cyclonic vorticity and enhance mesoscale cyclone activity. In the low levels, katabatic wind descent from the higher East Antarctic plateau to the lower Ross Sea/Ross Ice Shelf region helps to induce vertical stretching (Gallée 1995; Heinemann and Klein 2002). However, the vertical extent of these airflows is fairly small [only several hundred meters], so synoptic support is required to produce significant stretching over a larger layer (Heinemann and Klein 2003). In particular, support in the form of synoptic-scale advection of cyclonic vorticity and/or synoptic-scale warm air advection is required (Gallée 1995). Low tropospheric troughs provide a means for significant cyclonic vorticity advection (Carrasco and Bromwich 1993; Turner and Pendlebury 2002; Heinemann and Klein 2003). Low-level warm air advection produced by the synoptic circulation has been shown to play an important role in mesocyclone formation (Carrasco and Bromwich 1993; Carrasco et al. 2003). The warm air advection forms/enhances the baroclinic zone. Bromwich (1991) discovered that while synoptic forcing influenced formation, it was not required for cyclogenesis; however, upper-level support was key for subsequent development of the cyclones.

Surface fluxes of heat and moisture are also necessary. Gallée (1995) found that the sensible heat input from the ocean enhanced the temperature contrast in the boundary layer front created by the katabatic winds. Moisture fluxes are needed for the formation of large-scale, thick clouds and precipitation, usually in the form of snow. When the ocean is ice-covered, no significant mesocyclone activity or precipitation occurs (Gallée 1995). In this situation, other processes are required to produce mesocyclones, primarily, synoptic-scale circulation/support.

Finally, low-level convergence is produced at all three katabatic wind confluence zones. This convergence provides cyclonic shear necessary for mesocyclone initiation. The significance of these confluence zones and their katabatic winds to mesocyclone activity is illustrated in Figure 10.

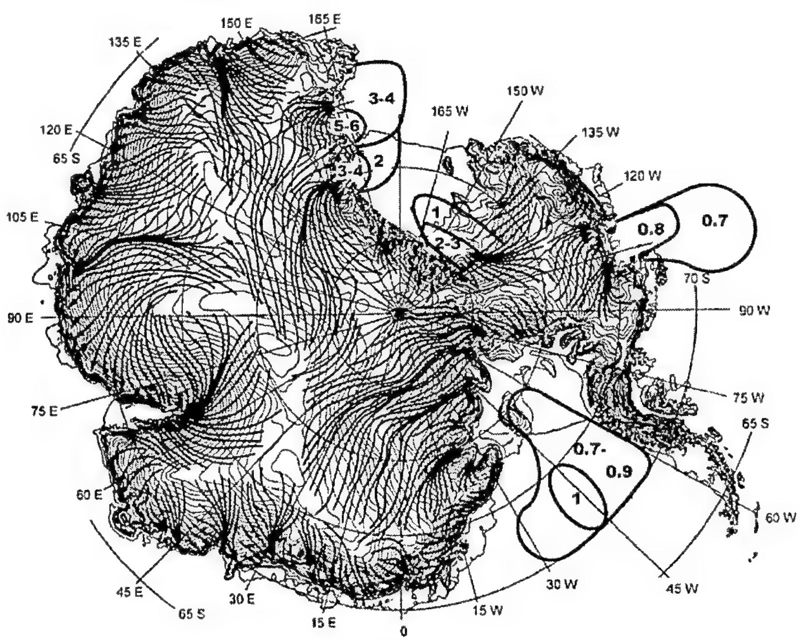

FIG. 10. Maximum normalized distribution of mesoscale vortices superimposed on simulated streamlines of katabatic wind drainage by Parish and Bromwich (1987) (Carrasco et al. 2003).

Mesocyclones have the ability to produce large amounts of snow, gale force winds, severe reductions in visibility, and significant turbulence and icing. The degree to

which these conditions affect McMurdo Station and USAP logistical operations depends on where they move after formation. Carrasco et al. (2003) described the prevalent mesocyclone tracks in the Ross Sea/Ross Ice Shelf Region (Fig. 11). Mesocyclones that

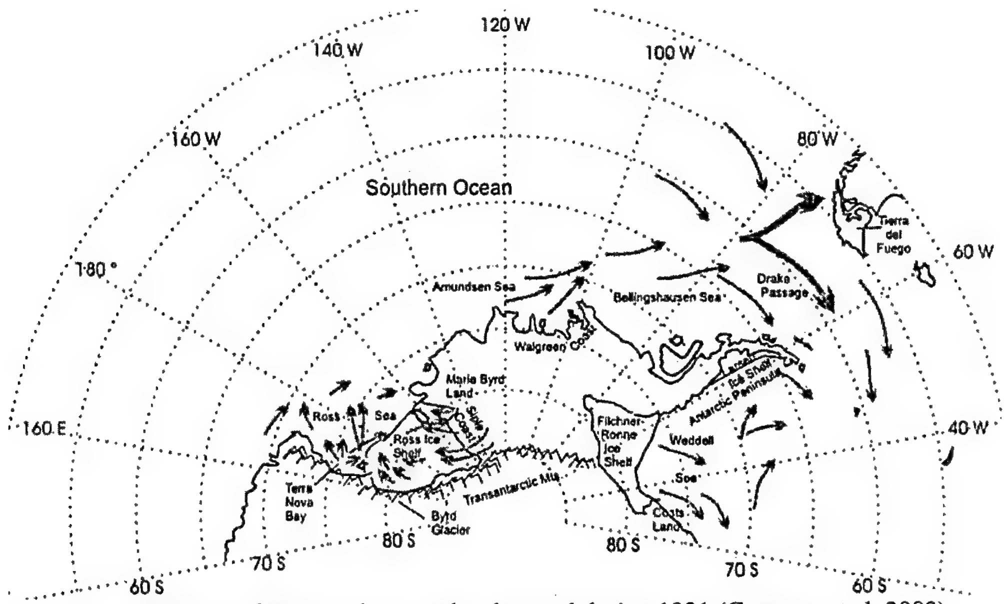

FIG. 11. Depiction of mesocyclone tracks observed during 1991 (Carrasco et al. 2003).

form around Terra Nova Bay generally move to the northeast or east-southeast. Byrd Glacier cyclones have a northeast tendency, while the Siple Coast storms move to the northwest, along the Transantarctic Mountains. All of these trajectories, except for the northeast track out of Terra Nova Bay, move the mesocyclones into the general vicinity of McMurdo Station. The track that probably causes the greatest threat to McMurdo is the one parallel to the Transantarctic Mountains. These cyclones have the potential to form barrier winds (O'Connor et al. 1994), which can put McMurdo in Weather Condition I. This kind of weather activity in the vicinity of McMurdo Station poses a great risk to the USAP's logistics operation, for both airlift and sea missions. It is vital that accurate forecasts are made for these conditions in order to ensure the safety and success of all USAP operations.

5. Analysis and Forecasting Tools

In order to better understand the previously mentioned meteorological features present in Antarctica and to create useful operational weather forecasts for USAP aviation activities, scientists have developed/adapted several different tools. These include in situ observational systems, most notably the continent-wide Automatic Weather Station (AWS) network, space-based remote sensing platforms, and numerical weather prediction models. Independently, they each present valuable information for respective levels of the atmosphere; however, combined together they generate a comprehensive dataset essential for accurate weather analysis and forecast production.

5.1. In Situ Observations

Surface observations of meteorological conditions have been taken on the Antarctic continent sporadically over the last 100 years. In the early part of the 1900s, Antarctic expeditions by Shackleton, Amundsen, and Scott [to name a few] provided extended, year-round surface observations from coastal camps for several consecutive years, respectively; however, consistent observations across Antarctica were not made until after World War II. The IGY of 1957-58 initiated a tremendous advance in in situ surface and upper air observations, with 12 nations establishing over 60 research stations in Antarctica, primarily along the coast (King and Turner 1997). Unfortunately, these manned stations were spread so far apart their observations were not useful for Antarctic forecasting.

Over the years, the total number of year-round stations has dropped dramatically, with a majority of the original stations closing down and only a few additional countries creating new ones. Currently, there are approximately 36 manned, year-round stations

operated by 18 different countries. These stations are concentrated on the coastal fringes of the continent, with a large majority in the Antarctic Peninsula region. This geographic placement is a function of Antarctica's harsh environment and the resultant cost of supporting an interior research station. Most of the 36 stations record surface observations, but only 13 make upper air observations [including the sole interior station, Amundsen-Scott]. These observations provide a general indication of the synoptic-scale circulation for weather analysis, but they fail to capture mesoscale patterns, which are of utmost importance to operational forecasters.

In order to improve the usefulness of the observational data and bridge the geographic gap between stations, a denser observation network was needed. Since manned stations could not meet this requirement for logistical and financial reasons, researchers turned to unmanned options, specifically automatic weather stations.

The basic AWS unit is comprised of a 3-meter tower with a horizontal instrument support at the top, a solar panel and an enclosure [for the controlling hardware and radio transmitter] in the middle, and batteries at the base (Figs. 12 and 13). The main sensors of the AWS include: an aerovane [top of tower; max wind: 64.8 m s^{-1}], a platinum resistance thermometer [top of tower; resolution: 0.124°C], two thermocouples [one at the top of tower and one 0.5 m from the surface; resolution: 0.05°C], humidity sensor [top of tower; resolution ~1%], and pressure transducer [in enclosure; accuracy: ±0.25 mbar] (King and Turner 1997). The AWS provides observations of air temperature, wind speed, wind direction, and pressure every 10 min and measures the relative humidity and 3 – 0.5 m temperature difference every 20 min (King and Turner 1997). The

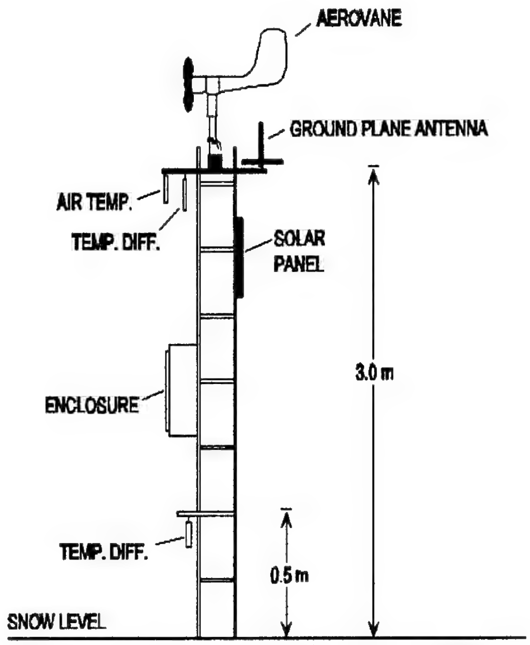

FIG. 12. Schematic of a basic AWS (AMRC).

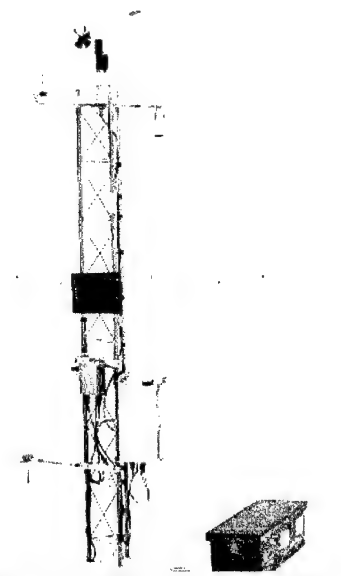

FIG. 13. Willie Field AWS from west (AMRC).

observations are sent to the ARGOS Data Collection System (DCS) on the National Oceanic and Atmospheric Administration (NOAA) polar orbiting satellites, via the radio transmitter located in the AWS enclosure, for transmission off the continent. The data is also immediately attached to the high-resolution picture transmission (HRPT), allowing near real-time reception by nearby Antarctic stations equipped with a steerable HRPT receiver, such as McMurdo (King and Turner 1997).

Before AWSs could be used with any success in the remote, severe Antarctic interior, advances in low-power electronics and satellite reception were needed (Turner and Pendlebury 2002). Low-power electronics allowed for the development of computers capable of operating in the Antarctic for long periods of time. The ARGOS DCS reception system ensured the data from these remote, unmanned AWSs was accessible to forecasters and researchers on and off the continent.

The ARGOS system consists of the radio transmitters at the AWSs, NOAA's polar orbiting satellites, three ARGOS ground (telemetry) stations, two global and several

regional processing centers (ARGOS 2001a; 2002). The AWS transmitter sends its observations in the blind at 200 sec intervals (AMRC 2004a). If a NOAA satellite is within range [line of sight] of the AWS, it receives the observation and stores it. When the satellite passes over one of the main ARGOS ground stations [Wallops Island, VA, Fairbanks, AK, or Lannion, France], it downloads the data (ARGOS 2001b). From the ground station, the raw data is passed to one of the two global processing centers [Largo, MD or Toulouse, France], where it is processed and then sent to a regional center (ARGOS 2002). From either the global or regional centers, the observation can be placed on the World Meteorological Organization Global Telecommunication System (GTS) for dissemination to the international meteorological community, especially the national forecasting centers. The USAP's AWS data has, since 1990, been placed on the GTS by a regional processing center, the Naval Oceanography Center in Monterey, CA (King and Turner 1997). Data archiving is accomplished at the global processing centers for up to six months; longer archives are maintained at the national forecasting centers (ARGOS 2002; King and Turner 1997).

The first AWSs were placed in Antarctica in 1980. Since then, over 100 have been deployed by various countries. The USAP's AWS network, which is the largest in Antarctica, is run by the University of Wisconsin-Madison's Antarctic Meteorological Research Center (AMRC). The AMRC retains all the raw data collected by their AWSs, past and present, which totals 113 units (AMRC 2004b). The data is received directly from the ARGOS global processing centers (King and Turner 1997). The data available for each AWS is not always complete or continuous. The operational lifetime of an AWS depends on the particular conditions it is subject to based on its location. Certain sensors

may fail before others, or the entire system may shut down at one time and because repairs can only be made during the austral summer, large time gaps in the data may occur. The AMRC currently has about 60 operational AWSs throughout Antarctica (Fig. 14). The location of the AWS units is determined by the meteorological experiments and

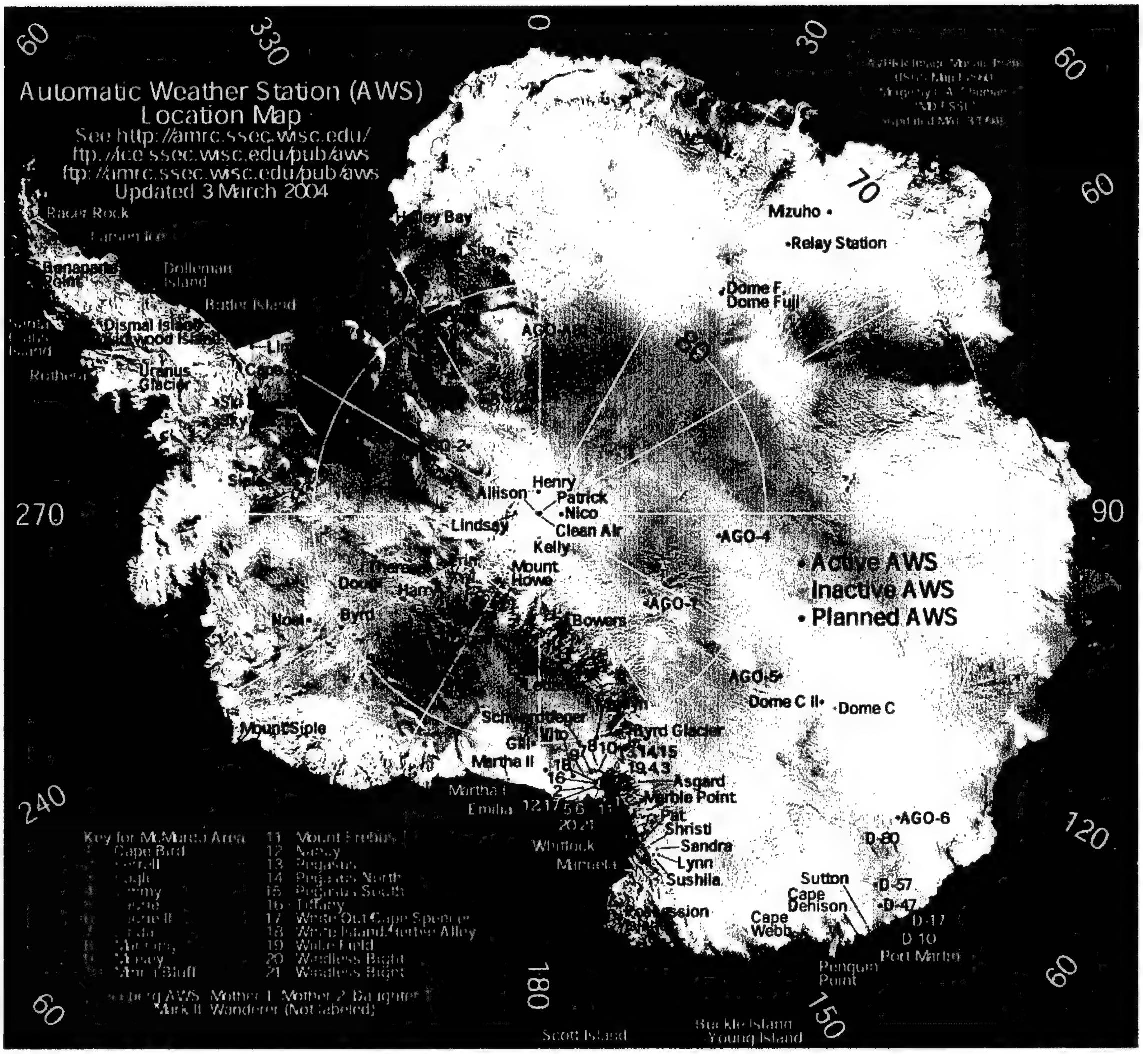

FIG. 14. AWS Location Map (AMRC).

operational missions they support (Stearns and Weidner 1994). Regardless of their primary mission, all AWSs contribute to meteorological support for inter- and intracontinental aviation activities.

McMurdo Station has 11 AWSs in its immediate vicinity as well as several more on the Ross Ice Shelf and surrounding area, which represents the greatest concentration of AWSs on the continent. These AWSs play an important role in supporting all aviation operations into and out of the station (Fig. 15). McMurdo forecasters receive data from these AWSs via two different methods. First, the station is equipped to collect observations directly from the 11 AWSs closest to McMurdo [line of sight], between Ross Island and Minna Bluff, providing a real time data display updated every 10 min (Turner and Pendlebury 2002). The second method, which is used for the surrounding AWSs, is reception from the HRPT transmission off the NOAA polar orbiting satellites.

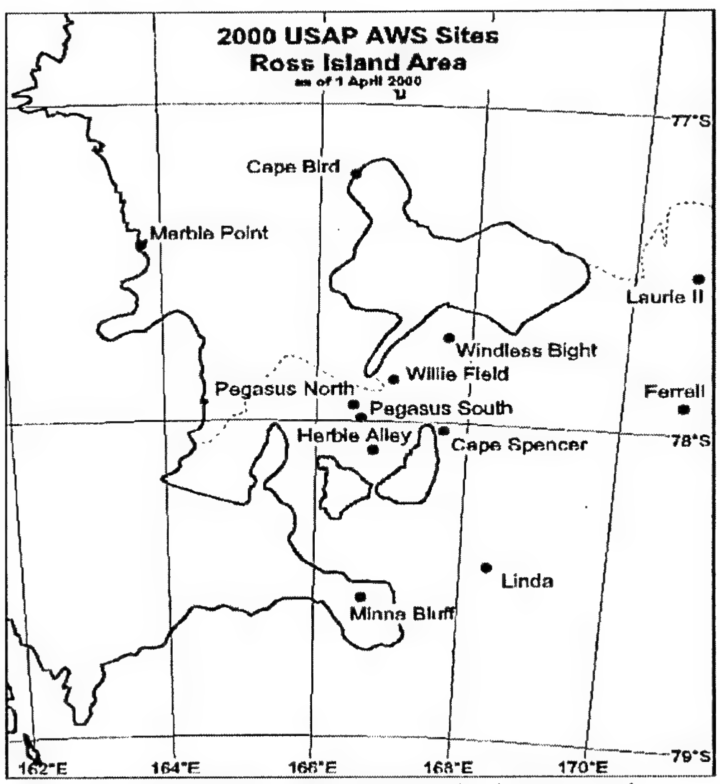

FIG. 15. USAP AWS vicinity of Ross Island (Turner and Pendlebury 2002).

The timeliness of the data has been essential to improving airfield forecasts at McMurdo. For example, the data received directly from the AWSs close to McMurdo have been used successfully in fog forecasts. In fact, McMurdo forecasters refer to these

AWSs as 'fog sensors' because when they report relative humidities greater than 80%, fog often occurs (Monaghan 2002). The AWSs, including those on the Ross Ice Shelf south of Minna Bluff, have also been helpful in creating empirical rules for high wind speed events at the airfields. As mentioned earlier, high wind speeds pose several problems for aviation operations at McMurdo. Holmes et al. (2000) conducted a study using AWS data to make short-term [3 – 6 h] forecasts of high wind speed events [greater than 15 m s^{-1}] for the Pegasus runway. They reviewed data from 10 AWSs over a six-year period and found 109 high wind speed events. Focusing on these events, they studied the data preceding each one to find common trends. Based on their study, Holmes et al. (2000) were able to derive several guidelines, that when used along with other forecast data available at McMurdo, will enhance the accuracy and lead time of high wind speed forecasts; in addition, their study proved the utility of AWS data for operational forecasting at McMurdo.

While the automatic weather stations have helped to fill the data gaps in Antarctica and proven very useful for operational purposes, there still exist several problems that need to be addressed in the future. First, even with the current AWS network, Antarctica is prohibitively lacking in observational data. This shortage is evident when compared to the continental United States. Antarctica has "one surface (upper air) observation per 413,000 km^2 (1,651,000 km^2), while the US has one surface (upper air) observation per 14,000 km^2 (103,000 km^2)" (Bromwich and Cassano 2001). Second, due to the extremely harsh environment in which the AWSs operate in, equipment failure can frequently occur for short or long periods of time. Certain failures are limited in duration and the affected sensor or AWS becomes operational again;

however, total failures cannot be fixed until the next field season. The result is even greater gaps in the AWS network and dataset.

Coupled with the physical lack of observations is the accessibility of the available data. Colwell and Turner (1999) used the Antarctic First Regional Observing Study of the Troposphere (FROST) project to make an assessment of the availability of Antarctic observations on the GTS. They found that only 85% of the daily observations made in Antarctica are transmitted through the GTS. Colwell and Turner (1999) offered a few suggestions why some data does not reach the GTS, including: the observations miss their time slots either during the relay to the DCS or the download from the DCS to the ground station; and data corruption or loss between the AWS, DCS, and/or ground station. Another possible reason is computer failure/outages at any stage in the data transfer pathway (Turner and Pendlebury 2002). Despite the problems, it is important to note the number of AWS observations transmitted exceeds the number of observations from manned stations (Bromwich and Cassano 2001). Furthermore, data from AWSs maintained by other countries are not currently available. This problem is most likely caused by financial and/or technological reasons. The decrease in manned stations on the continent necessitates full access to all AWS data available, USAP and non-USAP.

The lack of observational data also has a direct effect on the global atmospheric analyses made by major national centers as well as on numerical weather prediction models for Antarctica. Turner et al. (1999) compared global analyses from the National Centers for Environmental Prediction, the European Centre for Medium Range Weather Forecasts, the Australian Bureau of Meteorology, and the United Kingdom Met Office and found the largest discrepancy between the four analyses occurred over Antarctica.

Using data from FROST, they verified that the analyses of the synoptic situation over the Southern Ocean and coastal regions are of fairly high quality, but there were difficulties creating analyses over the interior of Antarctica. Turner et al. (1999) also identified that synoptic and meso-scale weather features have a major effect on meteorological parameters, but mentioned that little research has been done into these systems. During the Antarctic Weather Forecasting Workshop [detailed in Section 6.1], S. Pendlebury, J. Turner, and Y.-H. Kuo elaborated on the state of the national centers' analyses, with a focus on mesoscale processes. While they agreed the four analyses represented the synoptic situation over the Southern Ocean well, they highlighted the analyses' failure to capture the mesoscale features important to operational forecasting (Bromwich and Cassano 2001). The role of sparse observational data in this problem is two-fold: first, the lack of data results in poor analyses, especially for smaller weather features; second, without sufficient data it is difficult to determine which of the four analyses is the most accurate.

For numerical weather prediction (NWP), the limited data causes problems in both model initialization and verification. The models use the current atmospheric state as their initial conditions. This information is provided by the global atmospheric analyses from the national centers. As mentioned above, these analyses differ and their accuracy is not easily determined. Poor initial conditions lead to poor numerical weather forecasts. Overall, the global NWP models reasonably forecast the synoptic situation, but poorly represent the vital mesoscale features. In order to verify a model's performance, the normal procedure is to compare the model's output for a particular time with the

observed weather conditions at that time. The scarcity of observational data in Antarctica makes model verification difficult.

Regardless of the above problems, the AWS network has proven to be very valuable and has provided data for areas that would otherwise not be available. Future AWS improvements will only increase its positive impact on operational forecasting.

5.2. Space-Based Remote Sensing

The advent of Earth-observing satellites in the early 1960s initiated a tremendous advance in Antarctic operational weather forecasting. For the first time, forecasters had information for the entire continent and surrounding oceans and were not forced to rely solely on the sparse surface and upper air observation network. Although the initial imaging instruments were simple and only provided low-resolution visible and infra-red (IR) pictures, forecasters were able to view weather systems as well as determine information on storm structure (King and Turner 1997). The early satellite images also allowed for climatological investigations of weather events, particularly, the frequency of clouds and cyclones (King and Turner 1997). In the intervening years, the increased number of operational satellites and new, improved sensor capabilities have enhanced the quality and utility of satellite data for Antarctica and cemented space-based remote sensing as the key to accurate operational weather forecasting for the continent. In fact, the general consensus among USAP forecasters is that "if there were no satellite images available, they might as well shut down operations and not forecast" (Fogt 2003).

USAP forecasters depend on both polar-orbiting and geostationary satellites. The most useful data comes from three main sun-synchronous, polar-orbiting satellite

systems: NOAA's Polar Operational Environmental Satellite (POES) Program, the DoD's Defense Meteorological Satellite Program (DMSP), and the National Aeronautics and Space Administration (NASA) Earth Observing System. In addition, the USAP has access to several other systems, such as: China's Feng Yun (FY-1) series, the Russian Federation's Meteor system, and NASA's Sea-viewing Wide Field-of-view Sensor (SeaWiFS). Geostationary satellites from the U.S. and several other countries [Europe, Japan, China, India, and the Russian Federation] also provide limited data. In general, Antarctica is at the very edge of the geostationary satellites' field of view; however, along the satellite's longitude, data is available down to 70°S (Turner and Pendlebury 2002). The greatest benefit these satellites provide is extended coverage of portions of the Southern Ocean and East Antarctic coast.

NOAA's POES Program currently has six satellites in orbit. There are two primary satellites, NOAA-16 and NOAA-17, and four in standby/backup mode [NOAA-11, -12, -14, and –15]. The satellites operate approximately 800 km above the Earth and make about 14 complete orbits in one day (Turner and Pendlebury 2002). NOAA-16's ascending node time is 1408 and NOAA-17's is 2218 (NESDIS 2004). The ascending node is the local time when the satellite crosses the Equator in a northward direction. Each satellite carries eight instruments: the Advanced Very High Resolution Radiometer (AVHRR), the High Resolution Infrared Radiation Sounder (HIRS), the Advanced Microwave Sounding Unit-A (AMSU-A; includes two sensors –A1 and –A2), the Advanced Microwave Sounding Unit-B (AMSU-B), the Solar Backscatter Ultraviolet Radiometer (SBUV), the Space Environment Monitor (SEM), and the Search and Rescue (SAR) Instruments [SAR Repeater (SARR) and SAR Processor (SARP)] (POES 2000).

The DMSP has five operational satellites in orbit [F-12, -13, -14, -15, -16]. These satellites all orbit the Earth at 830 km (NESDIS 2004). F-13 and F-16 are the two primary satellites, with ascending node times of 1825 and 1956, respectively (NESDIS 2004). Each DMSP satellite has seven sensors: the Operational Linescan System (OLS), the Special Sensor Microwave/Imager (SSM/I), the Atmospheric Water Vapor Profiler (SSM/T2), the Precipitating Electron and Ion Spectrometer (SSJ/4), the Atmospheric Temperature Profiler (SSM/T), the Ion Scintillation Monitor (SSIES), and the Magnometer (SSM) (DMSP 2004a).

NASA's EOS has only two operational satellites, EOS-AM (Terra) and EOS-PM (Aqua). Both satellites orbit the Earth at an altitude of 705 km with Terra's descending node time at 1030 and Aqua's ascending node time at 1330 (TERRA 2003a; AQUA 2003a). Each satellite operates a different suite of instruments. Terra has: the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), the Clouds and Earth's Radiant Energy System (CERES), the Multi-angle Imaging Spectro-Radiometer (MISR), the Moderate Resolution Imaging Spectro-Radiometer (MODIS), and the Measurements of Pollution in the Troposphere (MOPITT) (TERRA 2003b). Aqua carries: the Advanced Microwave Scanning Radiometer-EOS (AMSR/E), the Moderate Resolution Imaging Spectro-Radiometer (MODIS), the Advanced Microwave Sounding Unit (AMSU; includes two sensors –A1 and –A2), the Atmospheric Infrared Sounder (AIRS), the Humidity Sounder for Brazil (HSB), and the Clouds and Earth's Radiant Energy System (CERES) (AQUA 2003b).

The data from these satellites are received at McMurdo Station via two routes. The first is direct reception at McMurdo by specially installed antennas and the second is

a ‘store and forward’ method where the satellite downloads its data to special sites on the globe [off the continent]; from there the data is forwarded to central facilities for processing before dissemination to the world, including McMurdo Station, through the Internet (Bromwich and Cassano 2000). Direct reception is the preferred method for Antarctic operations. McMurdo receives data from the POES and DMSP satellites directly using its HRPT/Real Time Data (RTD) ground stations (Lazzara et al. 2003). While the EOS satellites also have direct broadcast capability, they transmit their data on X-Band [18 GHz] at a significantly higher rate [15 Mbps] compared to NOAA and DMSP [1 Mbps] (AQUA 2003c; Bromwich and Cassano 2000). Currently, McMurdo does not have the capability to directly receive this valuable data and must use the store and forward approach, which significantly limits the amount of data they are able to acquire from the EOS satellites because of Internet bandwidth restrictions at the station (Bromwich and Cassano 2000).

The most critical satellite instrument for Antarctic meteorology is the imaging sensor: NOAA’s AVHRR, DMSP’s OLS, and EOS’s MODIS. AVHRR has a nominal spatial resolution of 1.1 km at nadir [the point on Earth directly below the satellite] and collects data over a 3,000 km swath (POES 2000; King and Turner 1997). AVHRR has five visible and IR channels available [0.6 μm, 0.9μm, 3.7μm, 11μm, and 12μm] (Turner and Pendlebury 2002). The AVHRR continuously broadcasts data from all five channels, with full resolution, as part of the HRPT broadcast (King and Turner 1997). OLS provides high resolution, 0.5 km, visible and IR images from a 3,000 km scan (King and Turner 1997). Unlike AVHRR, OLS only has two channels, visible [0.4 – 1.1μm] and IR [10.0 – 13.4 μm] (DMSP 2004b; King and Turner 1997). Below 60°S the DMSP

satellites transmit their data in the clear, instead of the normal encrypted signal (Turner and Pendlebury 2002). MODIS, which is a derivative of AVHRR, has 36 spectral bands ranging from 0.4 μm to 14.4 μm; the first two bands are imaged at a nominal resolution of 250m at nadir, while the next seven offer 500 m, and the remaining 29 provide 1 km, over a 2,330 km swath (MODIS 2004; Turner and Pendlebury 2002).

Antarctic forecasters rely on these high resolution visible and IR images for their day-to-day operations. These images "provide information on the location of synoptic and mesoscale weather systems, frontal bands and areas of cloud cover over the continent and surrounding sea areas" (King and Turner 1997). Additionally, the visible and IR images allow forecasters to prepare analyses for data-sparse areas of the continent, determine the accuracy of numerical model forecasts, monitor sea ice, and track storm systems, like mesocyclones, and clouds for short-term forecasts (Turner and Pendlebury 2002; King and Turner 1997). When combined with other available data, such as surface observations from manned stations and AWSs, the images become a powerful diagnostic tool (Turner and Pendlebury 2002) for identifying important weather features, to include: fog, katabatic winds, and precipitation. For example, thermal IR images and AWS data have been combined to successfully identify and monitor katabatic winds over the Ross Sea/Ross Ice Shelf region (Fig. 16). It should be noted that although the katabatic winds appear warmer than the surrounding surface, they are comparatively colder (Bromwich 1989). The warm signature is a result of the katabatic winds being well-mixed by turbulence, which makes the surface under the airflow appear warmer than the highly stratified, calm wind regions beside the airflow (Bromwich 1989). T. Parish and D.

Bromwich validated this phenomenon during instrumented flights of the katabatic wind regime near Terra Nova Bay in November 1987 (Bromwich 1989).

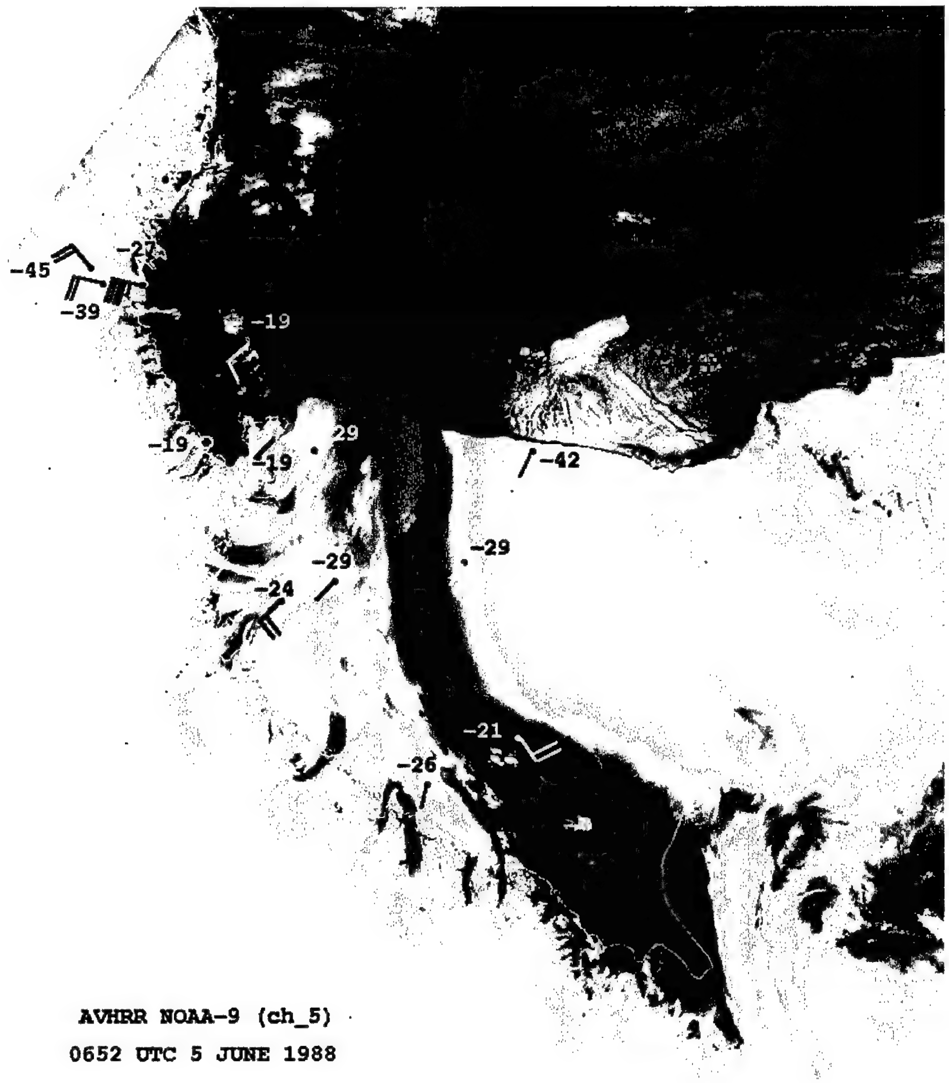

FIG. 16. Thermal IR image and AWS observations over the Ross Ice Shelf showing katabatic winds from glaciers in the Transantarctic Mountains and a katabatic surge from the Siple Coast (Polar Meteorology Group, BPRC).

Another powerful forecasting tool, derived from imaging sensor data on several polar-orbiting and geostationary satellites, is the AMRC's Antarctic Composites. These composite satellite images are mosaics of data from POES and DMSP as well as three geostationary satellite systems: the U.S. Geostationary Operational Environmental Satellite (GOES), the European Meteosat, and Japan's Geostationary Meteorological

Satellite (GMS) (Roth and Lazzara 2002). Three different images are produced every 3 h from 00 UTC: an IR Composite, a Water Vapor Composite, and a Visible Composite. Each composite is available in three different resolutions: low [20 km], mid [10 km], and full [5 km], with the low-resolution IR composite also color enhanced (AMRC 2004c). In addition to the single images, the AMRC provides Composite Movies of the last 24 h worth of images for the IR Composite [low and full resolution] and the Water Vapor Composite [low and full resolution] (AMRC 2004d). Both products are readily available on the AMRC's website: Composites at http://uwamrc.ssec.wisc.edu/realcomp.html and Composite Movies at http://uwamrc.ssec.wisc.edu/realmovie.html.

The composites have been produced by the AMRC since late 1992, with the support of the NSF (Lazzara et al. 2003). To create the composite, the AMRC uses images taken within 50 minutes before or after the hour, although most are ±15 minutes (Roth and Lazzara 2002). The calibration of all the images used is standardized so that temperature or color tones are constant across the composite (Roth and Lazzara 2002). The composites only use timely data, so if a certain region in the composite area is not covered during the set time window, it is left blank and appears black on the composite (Roth and Lazzara 2002). The composites "present a view of all weather systems and their motion over the Antarctic continent and southern oceans (from the South Pole to about 40°S latitude)" (Roth and Lazzara 2002).

The composites have proven to be very valuable for operational weather forecasting and research. An image from a single polar-orbiter (Fig. 17) only exposes a small portion of Antarctica, which may or may not be over the forecaster's area of

interest, but the composite provides a full view of the entire continent and surrounding ocean (Fig. 18). This allows the forecaster to see the big picture, synoptic-scale patterns

FIG. 17. NOAA-16 IR image, 29 APR 04 at 1651 UTC (AMRC 2004e).

FIG. 18. Full resolution IR Antarctic Composite, 29 APR 04 at 1500 UTC (AMRC 2004c).

and weather upstream of their location, as well as regional weather features. The Composite Movies provide even more information by showing how the weather systems and clouds have been moving over the last 24 h. This enables the forecasters to time systems and track developments. It also allows features that might not be discernable on a single image to stand out, such as clouds over the interior of the continent.

In addition to the visible and IR imaging sensors, the current operational polar orbiting satellites have several other useful instruments, including atmospheric sounders and passive microwave systems. While the visible and IR imagery allows the forecaster to observe weather systems and other cloud features, it does not provide any information on the vertical structure of the atmosphere, such as the temperature and water vapor profiles. This type of data is imperative to determine future atmospheric developments and it is also necessary as input into numerical weather prediction models, especially with the lack of radiosonde observations in Antarctica (King and Turner 1997). This is where

the atmospheric sounding instruments play a major role. The main sounding system is NOAA's Advanced Television Infrared Observation Satellites (TIROS) Operational Vertical Sounder (ATOV). This system is comprised of AMSU-A (-A1 and -A2), AMSU-B, and HIRS. DMSP satellites carry the SSM/T and the SSM/T2 and the EOS's Aqua has the AMSU and AIRS.

Passive microwave instruments are valuable because their data can be used to derive several important products, including the extent of sea ice, classification of ice by age, ice concentrations, snow accumulation rates, total precipitable water and cloud liquid water over the open ocean, ocean-surface wind speeds, and rain rates (King and Turner 1997; Turner and Pendlebury 2002). Microwave instruments have the ability to obtain these surface features through cloud cover, which is a major advantage in Antarctica due to its extensive, persistent cloud cover (Turner and Pendlebury 2002). The primary passive microwave instrument is the DMSP's SSM/I.

Satellites have been fundamental in the improvement of Antarctic operational weather forecasting over the last 40 years. They have been instrumental in increasing forecast accuracy, enhancing global and local atmospheric analyses, and improving global and mesoscale numerical models; however, there are still a few shortcomings that need to be resolved in order to fully harness the forecasting power satellites offer.

The most prevalent problem USAP forecasters confront on a daily basis is the lack of satellite data over the Ross Sea/Ross Ice Shelf region during their operational afternoon, approximately 2130 – 0400 UTC [1030 – 1700 McMurdo local] (Bromwich and Cassano 2000; Turner and Pendlebury 2002). The gap is a result of the satellites'

sun-synchronous orbit and its orbital optimization for considerations other than Antarctic operations (Bromwich and Cassano 2000).

Next to the daily data gap, the biggest problem is data reception. The EOS satellites, Terra and Aqua, collect a tremendous amount of data that could be extremely useful for Antarctic forecasting. Unfortunately, USAP forecasters are not able to directly receive this data at McMurdo, unlike NOAA and DMSP transmissions. Forecasters are forced to rely on the Internet for EOS data. This is not ideal because the current Internet link is only able to receive 1.544 Mbps [T-1], which the forecasters share with many other users (Bromwich and Cassano 2000). The result is an almost total loss of EOS data.

The final major problem revolves around data retrieval methods and products from existing satellite sensors. Current sensors like AVHRR have the ability to provide information on atmospheric properties like cloud opacity, phase, and effective particle size, while ATOVS and AIRS increases the amount of moisture and temperature retrievals available, all of which could be used for improving numerical model output; however, the retrieval algorithms were developed for middle or tropical latitudes and do not work as well in the Polar Regions (Bromwich and Cassano 2000; Lazzara et al. 2003). Additionally, there is a lack of derived products available to the USAP forecasters in real-time. These include: fog products, cloud detection, and satellite-derived winds. Most of these products, retrieved and derived, are produced off the continent and are not received in a timely fashion (Lazzara et al.).

Despite these issues, satellites are the primary tool USAP forecasters use to produce their aviation and operational forecasts. The forecasters rely on this data more than any

other forecasting tool available. Future improvements will only enhance the accuracy and value of the data and the forecasts they help to create.

5.3. Numerical Weather Prediction

In the 1970s, advances in computer technology ushered in the era of numerical weather prediction (NWP). Since then, continuous improvements in computing power/ability and our understanding of the atmosphere/ocean have brought NWP to the forefront of operational weather forecasting. NWP can be divided into two categories: global and limited area. Global models cover the world and have horizontal resolutions greater than 60 km, while limited area models [also known as mesoscale models] are typically focused on smaller areas and have horizontal resolutions less than 60 km. USAP forecasters have used both types of models to produce their forecasts, with varying degrees of success.

Prior to the 1999/2000 field season, USAP forecasters only had access to global NWP models. Specifically, they used: the Fleet Numerical Meteorology and Oceanography (FNMOC) Navy Operational Global Atmospheric Prediction System (NOGAPS), the National Centers for Environmental Prediction (NCEP) Aviation (AVN) model [now known as the Global Forecasting System (GFS)], the United Kingdom Meteorological Office (UKMO) model, and the European Centre for Medium-range Weather Forecasts (ECMWF) model. Overall, these models were "able to skillfully predict the evolution of synoptic-scale and larger atmospheric circulations, but [could] not reliably depict smaller-scale atmospheric circulations" (Bromwich and Cassano 2001; Pendlebury et al. 2003). These smaller-scale, or mesoscale, features are of primary

importance to short-term [less than 24 h] forecasts and aviation operations. The failure of the models to resolve these features was a result of the following problems: the models' horizontal resolution was too low, Antarctica's atmospheric physical processes were not properly represented, the continent's terrain and surface features were poorly depicted, and inadequate initial conditions were supplied (Bromwich and Cassano 2000).

Recently, global models have been adjusted in order to improve their prediction skill for mesoscale features. Turner and Pendlebury (2002) remarked that some of the global models' horizontal resolutions are approaching levels that were, only a few years ago, considered the domain of mesoscale models. Monaghan et al. (2003) compared four NWP models that were used during an early winter medical rescue mission at the South Pole. They found that the ECMWF had the highest overall skill. One reason attributed to the success of the ECMWF was its horizontal resolution, which, with respect to latitude, was 55 km; however, due to its Equal Lat-Lon projection, its resolution increased toward the poles, so that at 75°S its longitudinal resolution was ~28 km. Monaghan et al. (2003) found that the ranking of overall skill of the four models matched with that of their horizontal resolution. Despite these recent improvements, the suite of global models available does not adequately represent mesoscale disturbances to the degree required by Antarctic operational weather forecasters.

In response to this need, two mesoscale NWP models for Antarctica were introduced into USAP forecasting operations during the 1999/2000 season, a 45 km resolution model from the Air Force Weather Agency [AFWA MM5] and a 60 km resolution model from the Polar Meteorology Group of the Byrd Polar Research Center at The Ohio State University [Polar MM5] (Bromwich and Cassano 2001). The forecasting

potential presented by these models during the flying season prompted the NSF to request a meeting on the state of Antarctic operational weather forecasting and future changes necessary to continue to meet the USAP's needs. The Antarctic Weather Forecasting Workshop [discussed in Section 6.1] was held in May 2000. The common theme during the meeting was that accurate mesoscale modeling of Antarctica was possible and that it would significantly improve the overall forecasting skill for the continent and surrounding oceans, but first, several obstacles needed to be cleared. These included: the poor atmospheric analyses, especially of mesoscale features, which were used as initial conditions for the NWP models, lack of a robust data assimilation scheme, inadequate representation of Antarctic terrain in the models, and the use of improper physical parameterizations (Bromwich and Cassano 2001). Considering the complex terrain around McMurdo Station and the prevalence of mesocyclones in the Ross Sea/Ross Ice Shelf Region, a leading recommendation of the workshop was to design, in the short-term, a mesoscale model with a horizontal grid spacing of 15 km, with the ultimate goal of achieving a 1 km resolution model (Bromwich and Cassano 2000). This recommendation resulted in a joint project, funded by the NSF, between the Mesoscale and Microscale Meteorology (MMM) Division at the National Center for Atmospheric Research (NCAR) and the Polar Meteorology Group at BPRC to develop the Antarctic Mesoscale Prediction System (AMPS).

AMPS made its debut in the 2000/2001 field season as an experimental model. Despite this status, it quickly became the model of choice for USAP forecasters (Cayette et al. 2001). The goals of the AMPS project, as outlined by Bromwich et al (2003), are:

- to provide real-time mesoscale and synoptic forecast products for Antarctica, tailored to the needs of field forecasters at McMurdo station;
- to improve and incorporate physical parameterizations suitable for the Antarctic region into the forecast model (the MM5);
- to perform qualitative and quantitative forecast verification to assess the system's accuracy and to identify areas for model improvement; and
- to stimulate close collaboration between forecasters, modelers, and researchers by making the forecast products and the model output available to the community through a Web interface, public archive, and workshop/conference interactions

AMPS employs the BPRC's Polar MM5, a version of the fifth-generation Pennsylvania State University-NCAR Mesoscale Model (MM5), which has been modified for Polar Regions. The changes are based on research by the Polar Meteorology Group and have been previously used and tested over Greenland (Bromwich et al. 2001; Cassano et al. 2001). These modifications, as listed by Powers et al. (2003), include:

i. accounting for sea ice with specified thermal properties;
ii. representing fractional sea ice coverage in grid cells;
iii. using the latent heat of sublimation for calculations of latent heat flux over ice surface, and assuming ice saturation when calculating surface saturation mixing ratios over ice;

iv. modification of the CCM2 (Community Climate Model 2) radiation scheme to include the radiative properties of clouds as determined from the model's microphysical species (as opposed to relative humidity);

v. modified thermal properties of snow and ice (e.g., modified thermal diffusivity for snow-covered, permanent ice, and sea ice grid points); and

vi. more levels in the MM5's soil model (to better represent heat transfer through ice sheets)

Recently, Guo et al. (2003) completed an evaluation of the Polar MM5's performance over Antarctica from annual to diurnal timescales. They determined the Polar MM5 successfully represents both large- and regional-scale circulation features with generally small bias in the modeled variables. Guo et al. (2003) found the largest errors on the annual timescale included colder near-surface temperatures, deficient total cloud cover, and poor precipitation minus sublimation over the interior of the continent; while on the seasonal timescale the errors were a persistent positive surface pressure bias near the coast, a near-surface cold bias and a low-level dry bias in the interior, and a warm bias at upper model levels. Over all timescales, the Polar MM5 performed best in predicting the surface pressure, temperature, wind direction, and water vapor mixing ratio, but had difficulty with predictions of wind speed, missing many of the strong wind events (Guo et al. 2003). Regardless of these deficiencies, the Polar MM5 is adequate for studying Antarctica's atmospheric circulation.

Currently, AMPS is initialized twice a day, at 0000 and 1200 UTC. It provides output for several different domains. These include: a 90-km domain that includes

Antarctica and surrounding oceans up to 40°S [Fig. 19], a 30-km domain that covers the entire continent with mesoscale resolution [Fig. 20], two 10-km domains [one for the western Ross Sea/Ross Ice Shelf Region centered on McMurdo [Fig. 21] and one over the South Pole], and a 3.3-km domain, which is nested within the Ross Sea 10-km domain, over Ross Island [Fig 22]. Forecasts are provided in three-hour increments out

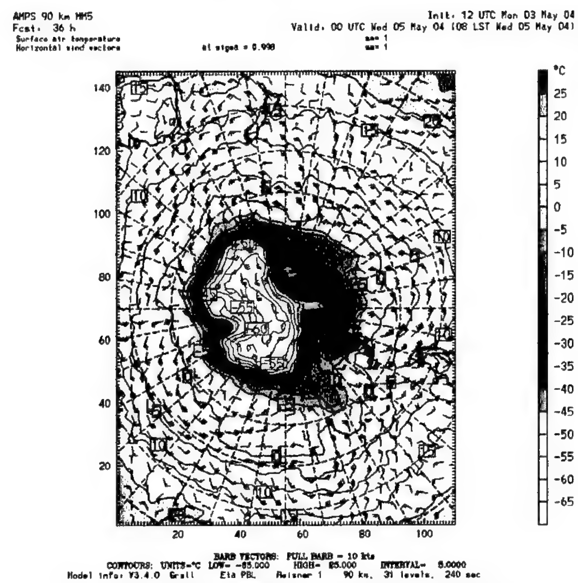

FIG. 19. AMPS 90-km domain, 36-hr surface forecast valid: 00 UTC 05 May 04 (AMPS 2004).

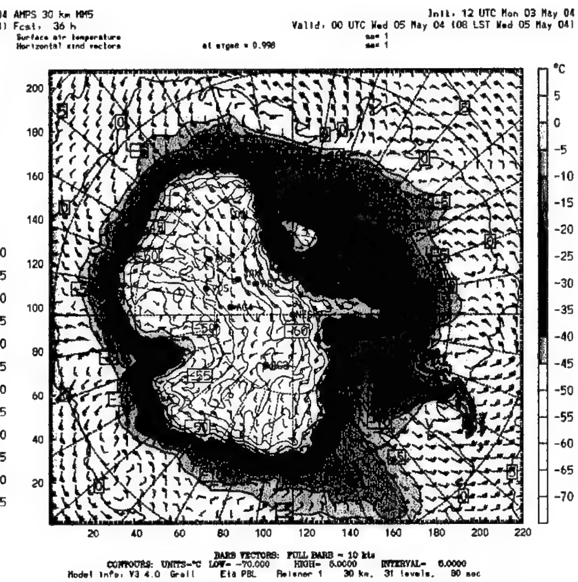

FIG. 20. AMPS 30-km domain, 36-hr surface forecast valid: 00 UTC 05 May 04 (AMPS 2004).

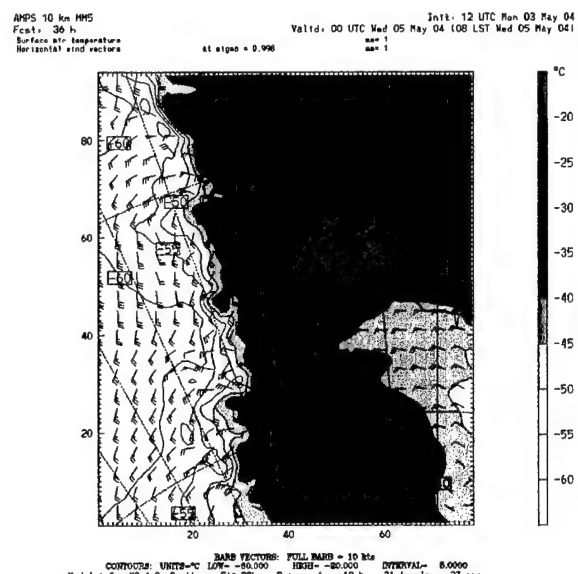

FIG. 21. AMPS 10-km domain, 36-hr surface forecast valid: 00 UTC 05 May 04 (AMPS 2004).

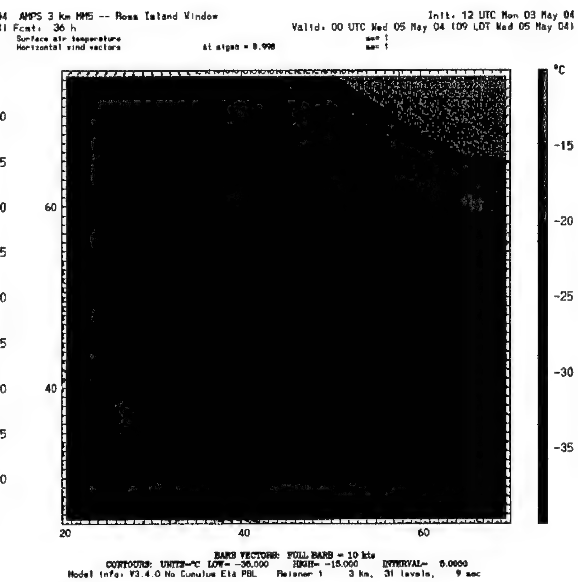

FIG. 22. AMPS 3.3-km domain, 36-hr surface forecast valid: 00 UTC 05 May 04 (AMPS 2004).

to 72 hr for the 90- and 30-km domains and 36 hr for the last three domains [forecasts begin at hour 6]. AMPS contains 32 vertical sigma levels, 11 of which are located in the lowest 1,000 m to capture the complex topography in Antarctic's boundary layer (Monaghan et al. 2004). Model topography is taken from a 5-km resolution digital elevation model, known as RAMP DEM, and the Ross Ice Shelf is represented as permanent ice (Monaghan et al. 2004). Initial and boundary conditions are taken from NCEP's GFS. The GFS first-guess field is objectively reanalyzed with the available observations [surface observations from manned stations and AWSs, upper-air observations, and satellite-derived cloud-track winds (for the 90-km grid only)] using a multiquadric technique (Powers et al. 2003). AMPS also ingests sea-ice data daily from the National Snow and Ice Data Center to initialize its fractional sea ice depiction (Powers et al. 2003). AMPS products are available through the Internet at http://box.mmm.ucar.edu/rt/mm5/amps/.

Since its inception for the 2000/2001 field season, AMPS has performed quite well for routine USAP aviation operations and special events [medevac and rescue missions]. During the 2001/2002 season, for instance, AMPS played a major role in the forecasts for 44 of the 53 occurrences of 'poor weather' [i.e., fog, snow, blowing snow, and/or low cloud layers] (Powers et al. 2003). The success of the model is a direct result of the efforts made by the research and operational communities. Case studies and model evaluations coupled with the daily scrutiny and feedback of the USAP forecasters has allowed AMPS to be continuously fine-tuned.

Bromwich et al. (2003) completed a case study on the success of the 10-km grid domain in forecasting a mesoscale cyclogenesis event in the western Ross Sea during

January 2001. They found the model was able to reproduce the development of observed upper-level conditions as well as resolve the many small-scale features prevalent in Antarctica, such as katabatic winds and mesolows/highs induced by the winds and topography of the Ross Sea/Ross Ice Shelf Region. Bromwich et al. (2003) also discovered the modeled storm tracks relied heavily on the quality of the GFS initialization, especially in regard to the position of upper-level forcing and the surface low pressure. The lack of observational data was mentioned by Bromwich et al. (2003) as the cause of inadequate initialization. Monaghan et al. (2003) also investigated the ability of AMPS during a medical rescue at the South Pole in April 2001. They compared the 30-km domain [which was the highest resolution over the South Pole at the time], with three other NWP models that were used during the operation: the GFS, the ECMWF model, and NCAR's Global MM5. Monaghan et al. (2003) found that all four models were successful in representing the free atmosphere, but closer to the surface skill levels became lower and more variable. As mentioned earlier, the skill of these models was directly proportional to their horizontal resolution, with AMPS being the second most successful model; however, Monaghan et al. (2003) are quick to point out that model performance is also a function of data assimilation, vertical resolution, and model physics. They also noted AMPS's sensitivity to the GFS initialization. USAP forecasters, for their part, have supplied a steady stream of valuable AMPS feedback through their operational interaction with the model and participation in workshops/conferences. Additionally, visits to McMurdo by BPRC graduate students (Monaghan 2002; Fogt 2003) have kept the lines of communication open between the

operational and research world and have fostered many substantial changes to AMPS, both internally and with the graphical output.

Improving the skill and accuracy of mesoscale numerical weather prediction models is a major focus of the Antarctic forecasting and research community. The next few years will provide critical enhancements that will secure AMPS as a premier forecasting tool for Antarctic operational weather forecasting.

6. Future of Antarctic Operational Weather Forecasting

The future of Antarctic operational weather forecasting has been the focus of considerable effort among Antarctic forecasters and researchers, from the United States and the international community, in the last several years. This has included two highly successful conferences focused on the practice of Antarctic operational weather forecasting, a comprehensive submission of recommendations to the NSF to improve all aspects of operational weather forecasting on the continent, and a proposal of a broad based field experiment to improve our understanding of Antarctica's physical processes and enhance the quality and accuracy of forecasting in Antarctica.

6.1. Antarctic Operational Weather Forecasting Conferences

The Australian Bureau of Meteorology (ABOM) and the British Antarctic Survey (BAS) organized the First International Symposium on Operational Weather Forecasting in Antarctica in the late summer of 1998. The symposium had 40 attendees, including forecasters, researchers, modelers and administrators, from eight countries involved in Antarctic research. The purpose of the meeting was to "review the methods used to prepare forecasts, to assess the new forms of data becoming available, to discuss the strengths and weaknesses of model output at high southern latitudes, and to identify areas where improved techniques are required" (Turner et al. 2000). The overall goal of the symposium was to "ensure that the many advances in our theoretical and practical understanding of Antarctic meteorology that have emerged in recent decades through the research community were being translated into improved forecasting techniques and methods" (Turner et al. 2000). The conference proved valuable in assessing the current

state of Antarctic operational weather forecasting and highlighted several areas that required further development, such as the overall lack of observations, limited transmission of available data, and the poor representation of mesoscale features in numerical models. Another key outcome of the meeting was the creation of the International Antarctic Weather Forecasting Handbook, which compiled the forecasting knowledge and experience of many countries into one source. The Handbook, which is edited by John Turner (BAS) and Stephen Pendlebury (ABOM), is currently in its third version, dated 23 September 2002.

In May 2000, the Antarctic Weather Forecasting Workshop (AWFW), initiated by the NSF's Office of Polar Programs, was held at the Byrd Polar Research Center (BPRC), The Ohio State University. The gathering was motivated by the "rapid growth of the USAP, the increasing reliance on heavy airlift capabilities in support of USAP goals, and recent advances in observational tools, numerical weather prediction, and other basic atmospheric science research in the Antarctic" (Bromwich and Cassano 2001). The workshop was structured to assess the current state of Antarctic atmospheric observations, weather forecasting, numerical weather prediction, and weather research, and to investigate future advances in Antarctic forecasting, with an overall emphasis on improving the safety and efficiency of USAP activities in Antarctica (Bromwich and Cassano 2001). The meeting was attended by over 50 participants, with diverse backgrounds and experience in Antarctic forecasting, from within the United States and several other countries.

At the conclusion of the three-day event, the members of the AWFW composed a detailed list of major recommendations for the NSF's consideration. These

recommendations addressed the main problem areas they had discovered: operational capabilities; meteorological information technology; training, skills, data, and people; numerical forecast models; and complimentary research and process studies. Two other important outcomes of the AWFW were the development of the Antarctic Mesoscale Prediction System (AMPS), discussed in Section 5.3, and a call for an extensive field program "to test existing forecast models, to provide model parameterizations tailored to [Antarctica], to provide a testing ground for new observational approaches from space and the surface, and to provide detailed understanding of mesoscale cyclogenesis and katabatic airflow dynamics" (Bromwich and Cassano 2001). The program will be centered on McMurdo Station and the surrounding area, and has been named the Ross Island Meteorology Experiment.

6.2. Necessary Improvements

The problems facing Antarctic operational weather forecasting are widely known and agreed upon by those engaged in forecasting and research in Antarctica and were highlighted and discussed during the two conferences detailed above. The solutions offered to resolve these problems are also consistent across the community. The AWFW articulated, with great detail, these necessary improvements with their recommendations to the NSF. This paper focused on three primary areas of concern: in situ observations, space-based remote sensing, and numerical weather prediction. The following solutions are, therefore, directed toward these three topics.

The foundation for most operational weather forecasting problems in Antarctica is the lack of observational data. Several steps need to be taken to help reduce this gap.

First, additional AWSs must be placed in Antarctica, especially in the larger data void regions. Second, these AWSs need to take advantage of new technologies and improved hardware reliability, extending their operational lifetime. Third, other observing instruments, such as drifting buoys, sonic radars (sodar), radio acoustic sounding systems (RASS), radar wind profilers, lidar systems, and polar atmospheric emitted radiance interferometers (PAERI), need to be utilized (Bromwich and Cassano 2001).

Fourth, inter- and intracontinental communication needs to be improved. All AWSs observations, USAP and non-USAP, must be placed on the GTS and made available to the national centers and all other interested parties. Additionally, communication between Antarctic research stations should be robust enough to pass weather information in real time, without having to go to a source off the continent. Moreover, the new AWSs should be designed with the capability to transmit directly to Antarctic weather stations via high frequency or very high frequency radio transmissions (Bromwich and Cassano 2000). The new AWSs should also be equipped with the new ARGOS-III system, which will have two-way communications between the transmitter and the satellite and a higher data transfer rate (Bromwich and Cassano 2000). This will allow the transmitter to only send its data when a satellite is available, instead of continuous transmissions.

Finally, methods should be employed to improve and extend the AWS datasets already available. One such process, successfully performed by Reusch and Alley (2002), used multilayer feed-forward artificial neural networks along with GCM-scale meteorological datasets [ECMWF 15-yr reanalysis] to predict surface parameters, specifically temperature and pressure, for gaps in the Ferrell AWS dataset between 1979-

1993. Another successful procedure, for surface air temperature only, was performed by Shuman and Stearns (2001). They combined surface temperature observations from four of the longest running AWSs in West Antarctica [Byrd, Lettau, Lynn, and Siple] with satellite passive microwave brightness temperature records to accurately fill in the data gaps in each of the AWS's datasets; thereby generating decadal-length, daily average, temperature records for the four AWSs. Filling data voids caused by equipment failures and extending AWS datasets after operational lifetime and, even, before initial installation will improve the quality and utility of the current AWS datasets. Extended, accurate datasets could be used to improve reanalysis products over Antarctica, to help verify numerical weather prediction models, and to construct meaningful climatological tables, all of which will provide forecasters with more complete information to meet the forecasting challenge presented by Antarctica.

Along with enhancing the in-situ observation network and dataset, improvements are necessary in Antarctica's space-based remote sensing operations. A major advancement, the National Polar-orbiting Operational Environmental Satellite System (NPOESS) is already in the planning/implementation phase. NPOESS will combine NOAA's POES Program, the DoD's DMSP, and NASA's polar-orbiting program into a unified U.S. polar-orbiting system (NPOESS 2002). NPOESS will consist of three satellites, two from the U.S. and one, called MetOp, from the European Space Agency and will use a mix of new and existing sensors. The program will begin to phase in around 2005 and is projected to last through 2018 (NPOESS 2002). The new suite of sensors will provide Antarctic forecasters with a wealth of information.

Besides NPOESS, there are several other satellite programs that are planned to launch in the near future, including: the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) program, NASA's Triana spacecraft, Japan's ADEOS-2, and China's Feng Yun 3 (FY-3) (Bromwich and Cassano 2000, Turner and Pendlebury 2002). The USAP needs to evaluate the usefulness of these satellites and maintain the ability to access their data (Bromwich and Cassano 2000).

In addition to new satellite programs, there are several satellite data challenges/problems that need to be corrected in order to improve USAP forecasting. The most significant problem is McMurdo's daily satellite data gap. This problem can be resolved by several means.

First, data from the EOS Terra and Aqua satellites needs to be available via direct broadcast at McMurdo Station. This will require a ground receiving station capable of receiving in X-Band. Currently, McMurdo is home to the McMurdo Ground Station (MGS), which meets this requirement. In the past, the MGS has been primarily used to receive data from Synthetic Aperture Radar (SAR) satellites and to support satellite and spacecraft commanding (MGS 2004). Recently [09-11 March 2004], a workshop was held by the AMRC and BPRC to discuss "the capabilities of the next generation satellite fleet along with applications and reception possibilities with a focus on the MGS, especially as it relates to USAP research and operation activities" (MGS 2004). The results of that meeting have yet to be released, but hopefully they will help to pave the way toward utilizing the MGS for meteorological purposes.

Additionally, acquiring X-Band reception capabilities will allow USAP forecasters access to other satellites that are not currently available to them, such as

NASA's Landsat-7 and QuikScat, Canada's RADARSAT, Europe's Envisat, ERS-1, and ERS-2, and India's OceanSat-1 and IRS series (Turner and Pendlebury 2002). The direct reception of all this data will eliminate the time-consuming 'store and forward' method of data collection, which will help to reduce the data gap over McMurdo. In the long term, the new satellite programs mentioned above should also help to minimize this gap.

With all this satellite data locally available, the USAP's forecasters will need to have the ability to process the data and derive useful products at McMurdo. This will require increased computer facilities, but most importantly, it will require accurate Antarctic retrieval and derivation algorithms/methods. Properly creating these procedures will require large amounts of in situ surface and upper-air data. Once the algorithms/methods are created they will need to be validated before they can be used with any confidence. A task like this will require substantial, dedicated fieldwork with a vast, modern observation network. Such a field program is currently in the early stages of development and is discussed in Section 6.3.

All of the advances mentioned above for in situ observations and space-based remote sensing will go a long way toward improving NWP for Antarctica. These two immense data sources will provide the means to address several problems areas within Antarctic numerical weather prediction.

The first step will be to improve the assimilation of this data. Bromwich et al. (2003) and Monaghan et al. (2003) both remarked on AMPS's sensitivity to the GFS initialization. They each ran AMPS using ECMWF analyses for the initial and boundary conditions and found significant differences in the placement and movement of surface mesoscale features. While the overall forecasts in these runs were not substantially better

than the AMPS-GFS runs, it should be noted that the ECMWF analyses have a much lower spatial and temporal resolution than the GFS output (Bromwich et al. 2003; Monaghan et al. 2003). The success of the ECMWF lies in its use of four-dimensional variational data assimilation [4DVAR] (Monaghan et al. 2003). Bromwich et al. (2003) proposed that increased observational data assimilated into AMPS using a variational approach [such as 3DVAR or 4DVAR], instead of the current multiquadric technique, would help to improve the mesoscale initialization. They also emphasized that increased upper-level observations would provide a more consistent enhancement and focused on the need to assimilate satellite-derived measurements and products.

Continued improvements in AMPS's physical parameterizations are also required. This will require detailed, process-oriented observations (Bromwich and Cassano 2000) over a sufficient length of time to determine if the current parameterizations are valid. For those that are not usable, new parameterizations will need to be developed using the data collected. Furthermore, validation of the new parameterizations will be necessary before they can be used. This process is very similar to that required for satellite retrieval and derivation algorithms/methods. As such, the RIME field experiment, detailed below, with be able to satisfy both requirements at the same time.

In addition to verifying specific physical parameterizations, overall validation of the AMPS output is essential. The improved datasets provided by in situ observations and space-based remote sensing will supply the information required to accurately assess the model's output.

Finally, the operational and research weather communities need to continue to strive toward the goal of a 1 km resolution mesoscale model over Antarctica, especially

the Ross Sea/Ross Island Region. Increasing the resolution will require enhanced computational capacities, improved terrain and land use data, accurate parameterizations, and a large dataset for verification. All of these prerequisites will be provided/gained during the upcoming RIME project.

6.3. Ross Island Meteorology Experiment

Most of the improvements listed in Section 6.2 will require extensive field work/measurements before they can be realized. The AWFW proposed one such field project at the conclusion of their meeting, the Ross Island Meteorology Experiment (RIME). RIME is currently in the planning process and will be "a basic and applied research program to explore in detail the atmospheric processes over Antarctica and their interactions with lower latitudes via the Ross Sea sector" (Bromwich and Parish 2002). While the scientific motivation behind RIME is focused on linking Antarctic processes with their role in global climate change and teleconnections to the rest of the hemisphere, it will have a direct, positive impact on operational weather forecasting in Antarctica, especially for USAP operations in and around McMurdo Station, which is in the heart of the RIME study area. According to Bromwich and Parish (2002), RIME will have two primary objectives:

- To better understand key phenomena such as boundary-layer dynamics, topographic modification of synoptic and mesoscale features, cloud-radiation interactions, and moist processes accompanying episodes of cyclogenesis over the Ross Sea

- To conduct detailed measurements of key physical processes in the boundary layer and free atmosphere to permit the development of accurate parameterization schemes for use within numerical models, leading to high quality simulations

The fundamental goal of RIME will be "to study the physical processes in the lower atmosphere and transports of heat, momentum, and moisture within the Ross Sea sector during episodes of extratropical cyclone forcing and accurately simulate these within numerical models" (Bromwich and Parish 2002).

RIME will consist of observational and modeling components on both a regional and local scale. The regional scale will encompass the area bounded by the RIME baseline stations of Terra Nova Bay, Dumont D'Urville, Dome C, Amundsen-Scott, and McMurdo, while the local scale will include the region within a 100 km radius of McMurdo. The regional study will "focus on the circumpolar vortex about Antarctica, terrain-induced motions and transports, cyclone forcing in the Ross Sea sector, and mesoscale cyclogenesis" (Parish and Bromwich 2002). The local study will "emphasize details of the horizontal and vertical atmospheric structure about Ross Island and the energy exchanges within the boundary layer, moisture fluxes and smaller-scale modulation of the low-level airflow by the adjacent topography" (Parish and Bromwich 2002).

The observation component of RIME will be comprised of an enhanced AWS network, routine radiosonde launches, tethersondes, data from automated geophysical observatories, drifting buoys, ship observations, surface-based remote sensing [PAERI, sodar, lidar, profilers, etc.], micrometeorological and flux towers, space-based remote

sensing [AVHRR, TOVS, SSM/I, MODIS, SAR, etc.], and instrumented fixed wing aircraft and helicopters [considered vital for RIME success] (Bromwich and Cassano 2000; Parish and Bromwich 2002). This concerted measurement effort will produce a comprehensive dataset that will be valuable not only to RIME, but to future research projects.

The modeling component of RIME will use this dataset to perform several evaluations over a range of topics, to include: data assimilation, parameterization processes, forecast sensitivity studies/adjoint modeling, and model intercomparison. Some of the key goals for this component are: to determine the accuracy of current satellite retrieval algorithms, for the various polar orbiting satellites used in Antarctica; to assess the most effective process for assimilation of satellite data into numerical models; to evaluate current model parameterizations for accurate representation of the Antarctic environment and its atmospheric processes; to formulate new parameterizations to better represent Antarctic processes, specifically for clouds, surface energy budget, turbulent and wave processes, and boundary layer development; to determine the optimal blend of in-situ and space-based observations necessary to improve numerical weather prediction in Antarctica; and finally, to initiate a model intercomparison project of the models currently used in Antarctica (Parish and Bromwich 2002).

RIME will have two field seasons [Dec 2005 – March 2006 and Sep – Dec 2007] and two analysis phases [Mar 2006 – Sep 2007 and Jan 2008 – Jun 2010]. Planning is on-going; the Second RIME Implementation Workshop was held from 07 – 09 Apr 2004 at the National Center for Atmospheric Research in Boulder, CO.

7.0. Conclusion

Antarctic research has and will continue to achieve major advances across many different scientific disciplines. Unfortunately, due to Antarctica's remote location and severe weather, this research requires immense logistical resources and coordination. The USAP funds and maintains a comprehensive logistics operation to ensure researchers receive the support they need. The heavy airlift capability of the U.S. Air Force Reserve and Air National Guard perform a critical role in this logistical operation, known as Operation Deep Freeze. Their flights from Christchurch, New Zealand to McMurdo Station, Antarctica and from McMurdo to the South Pole and various field camps ensure personnel and supplies reach their destination safely and efficiently. Accurate weather forecasts from USAP forecasters for the harsh, unforgiving environment of Antarctica are critical to the success and safety of Operation Deep Freeze missions. In order to create their forecasts, the USAP relies on analysis and forecasting tools created for Antarctica, specifically the continent's in situ observation network, space-based remote sensing, and numerical weather prediction. Each has provided tremendous amounts of information to increase the utility of USAP forecasts, but problems still exist. Future improvements are necessary to ensure that Antarctica's unique weather patterns are better understood and, thereby, accurately forecasted. Implementing all of the solutions outlined in this paper will take substantial funding, time, dedication, and international cooperation; however, successfully achieving them will provide tremendous advances in Antarctic operational weather forecasting. In turn, this will help secure the safety and success of the USAP's logistics operation and enable our Nation to attain its goals in Antarctica.

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